OPTIMAL OPERATION OF MULTIRESERVOIRS-IN-SERIES WITH STOCHASTIC INFLOWS

A Thesis Submitted
in Partial Fulfilment of the Requirements
for the Degree of
DOCTOR OF PHILOSOPHY

By

N. H. MODI

to the

DEPARTMENT OF CIVIL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY KANPUR

OCTOBER 1982

Dedicated to

my parents

CERTIFICATE

This is to certify that the thesis entitled "Optimal Operation of Multireservoirs-in-Series with Stochastic Inflows" submitted by Shri N.H. Modi, in partial fulfilment of requirements for the Degree of Doctor of Philosophy at the Indian Institute of Technology, Kanpur is a record of bonafide research work carried out under my supervision and guidance. The work embodied in this thesis has not been submitted elsewhere for a degree.

V. Lakshminarayana
Professor
Department of Civil Engineering
Indian Institute of Technology
Kanpur.

9/7/1983

ACKNOWLEDGEMENTS

I express my profound gratitude to my supervisor Dr. V. Lakshminarayana for introducing the problem and providing the necessary guidance throughout the course of this work.

I am very much thankful to all my fellow research scholars Messrs H.K. Patel, P.G. Poonacha, K.V. Jaykumar and H.S. Ningappa for their help and support from time to time. In particular, I thank Mr. K.V. Desikachar, S.P. Sharma and M.P. Oza for carefully going through the major portion of the type script.

I am thankful to the Director of Technical Education, Gujarat State for sponsoring me under the Quality Improvement Programme and the authorities of I.I.T. Kanpur for providing the research facilities.

I appreciate my wife Dhanlaxmi for shouldering the entire family responsibilities during the period of my stay at I.I.T. Kanpur. I appreciate the forbearance of my daughters Tripti, Sejal and Kinjal throughout the period of this work. I owe to my parents for their co-operation.

I express my sincere thanks to my friends Messrs N.C. Tilvawala, Dr. R.D. Patel, Rajanibhai Patel and P.M. Pandya for taking care of my family during the period of my stay at I.I.T. Kanpur.

I am thankful to Shri R.N. Srivastava for efficient typing and Shri A.K. Ganguli for good tracing work.

N.H. Modi

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATION

$a_{i,t}$	Release to meet irrigation requirements at reservoir site i, during time t
b_j	Least square regression coefficient for the j^{th} season
$b_{i,t}$	Coefficient (derived from the relationship between economic loss and water shortage)
B	Net annual benefits
ΔB	Change in benefit
b_1	Constant for irrigation in loss function
b_2	Constant for energy in loss function
$c_{i,t}$	Release to meet energy requirements at reservoir site i, during time t
C_t	Correlation component of streamflow
$C_{1,t}$	Annual capital cost of irrigation work at site i
$C_{2,i}$	Annual capital cost energy generation at site i
$C_{3,i}$	Annual capital cost of reservoir at site i
C_5	Proportionality constant
D_i	Dead storage at site i
d	Distance from original base to revised base
E_i	Firm energy target at reservoir site i
E	Energy in kwhr
e	Efficiency of turbine and generator
$EB_{2,i}$	Gross annual energy benefits at site i
$f_{i,t}$	Inflow due to independent catchment area of reservoir site i, and during time t
g_i	Coefficient of skewness of flow during month j
h	Head acting on turbine in feet
I_i	Annual irrigation target at reservoir site i

$IB_{1,i}$	Annual gross irrigation benefit at site i
IR	Irrigation benefits in Rs. 10^7/MAF
IRR	Actual water supplied to irrigation in MAF
j	Year number at each site i
K_i	Normal standard deviate
$K_{i,t}I_i$	Proportion of irrigation demand I at reservoir site i and during time t
$K'_{i,t}I_i$	Return flow from irrigation utilisation at reservoir site i, during period t
K_1	Coefficient used in loss function
K_5	Constant value used in steepest ascent method
L	Total loss in T periods
L_t	Loss in period t
L_{IRR}	Total loss for irrigation in 10^7 rupees
L_{ENG}	Total loss for energy in 10^7 rupees
n	Station number
N	Number of years
N_t	Number of consecutive shortages in period t
$O_{1,i}$	OMR cost of irrigation at site i
$O_{2,i}$	OMR cost of energy at site i
$O_{3,i}$	OMR cost of reservoir at site i
p	Number of sub-period i in period t
PE	Energy price/kwhr
q_i	Small increment in flow for month i
Q_i	Recorded flow for month i
Q'	Quantity of water passing through turbine in cfs
R_i	Correlation coefficient for month i
SE_t	Periodic component of streamflow for period t
S_j	Standard deviation of flows for jth season

ST_i	Reservoir content in month i
$SH_{i,t}$	Shortage in sub-period i (positive or otherwise zero) in period t
SHI	Shortage index
SH_t	Shortage in period t
$\overline{SH}$	Average shortage
SHI1	Shortage index for irrigation
SHI2	Shortage index for energy
$\overline{SH_1^2}$	Average of squared shortage ratio for irrigation
$\overline{SH_2^2}$	Average of squared shortage ratio for energy
T_t	Trend component of streamflow for time t
t_i	Normal Random variate of zero mean and unit variance
T	Total period
W	75% dependable flow
X_i	Annual runoff for period i
X_t	Monthly flow for time t
X_t'	Standardized monthly flow for time t
$\overline{X}$	Mean annual runoff
ΔX	Increment in design variable
Y_i	Gross reservoir capacity at site i
Y_t	Quantity of water supplied for period t
Y_t'	Quantity of water required for period t
Z	Random number

Greek

α_1	Coefficient used in loss function
β	Beta coefficient used in HEC-4 model
γ	Annual Lag-one coefficient

$\delta_t E_i$	Proportion of energy demand E at reservoir site i during period t
ε_t	Random component of streamflow
$\emptyset_t$	AR parameters
ν_t	Coefficient of skewness
$INB_{1,i}$	Net annual benefit from irrigation at reservoir site i
$ENB_{2,i}$	Net annual benefit from energy at reservoir site i

SYNOPSIS

OPTIMAL OPERATION OF MULTIRESERVOIRS-IN-SERIES
WITH STOCHASTIC INFLOWS

A Thesis submitted
In partial Fulfilment of the Requirements
For the Degree of
DOCTOR OF PHILOSOPHY
by

N. H. MODI
to the
Department of Civil Engineering
Indian Institute of Technology, Kanpur, India

The combined use of optimization and simulation techniques proves to be efficient for planning and designing of large water resource systems. Optimization technique selects the best out of many generated alternatives for a specified objective, while simulation attempts to study the performance of a specific alternative. These techniques are applied, in this thesis, to the Narmada river basin in the central zone of India. The system consists of five serially linked reservoirs located on the main stem of river. A mathematical model is used to represent the main features of the system. Four periods in a year are selected for use in the discontinuous linear programming (LPD) model. ZX3LP (IMSL) computer package program available on DEC 1090 computer system is used to run the LPD model. This model is implemented for different cases such as different configurations, different flow conditions, linear and nonlinear objective functions, etc., to obtain 14 design variables namely, gross reservoir capacities, seasonal water releases for irrigation and

installed capacities of power houses. Deterministic inflows are used. LPD is used in the preliminary design stage.

If the system analysis is based only on the LPD model, the design of system may be overoptimal or underoptimal. Hence the results of the LPD model are needed to be screened further. A range for each variable is assumed on the basis of the results of the LPD model for use in steepest ascent method of sampling. A set of design variables from this range is selected arbitrarily as an initial base. The jump or step value is set to about one-fifth of its range for each variable. The step values are decreased in successive iterations. A nonlinear objective function developed for LPD model is used to represent the response surface. A net maximum annual benefit of Rs. 120.65 x 10^7 is obtained. The set of variables which gives maximum net benefits is selected for simulation study. Values of the selected variables namely gross storage in MAF, annual irrigation target in MAF and installed capacity in MW for each reservoir are 6.25, 4.00, 9.00 (Bargi), 14.82, 10.30, 240.00 (Narmadasagar), 1.60, 4.14, 108.00 (Omkareshwar), 0.41, 0, 67.00 (Maheshwar), 7.76, 9.52, 125.00 (Sardar Sarovar) respectively. Maheshwar reservoir is designed only for hydropower and hence irrigation component is zero.

A computer program developed by HEC (1966) namely 'Reservoir Yield' is modified suitably, to fit the present system for simulation. Simulation attempts to study the performance of a system for specified operating policies. The operating policies include: (i) water release policy (ii) the maximum

and minimum permissible storages for each period and for each reservoir. Simulation study requires long sequences of streamflows. Since only 28 years of streamflow record is available at gauging sites at Jamtara, Mortakka and Garudeshwar, synthetic flows are generated using stochastic hydrology preserving important statistical parameters of the historical streamflows. HEC-4 computer program: 'Monthly streamflow simulation' is used to generate 250 years of synthetic flows at each reservoir site, using transferred streamflow data available at each reservoir site.

Two types of simulation studies are made: (i) monthly simulation and (ii) flood simulation. Four monthly simulation runs are taken for NWDT award with and without modification, using historical and synthetic flows (NWDT: Narmada Water Disputes Tribunal). Rigid rules are developed for each reservoir using end of month storages. Shortage index and types of shortages for irrigation and power are evaluated at each reservoir site and for each simulation run. Loss functions are necessary to take into account the contingency of not being able to meet irrigation and power targets. Monthly statistics of spills from the terminal reservoir namely Sardar Sarovar are evaluated for each simulation run. The net average annual benefits from the system are Rs. 66.37×10^7 and Rs. 73.93×10^7 for modified NWDT. and NWDT award respectively for monthly simulation. In the case of flood simulation the net annual benefits are Rs. 71.53×10^7, and Rs.80.13×10^7 for modified NWDT and NWDT award respectively.

Flood simulation study is carried out to find the maximum 3-hourly spill from the terminal reservoir namely Sardar Sarovar. The Lag method of flood routing is used for channel routing. A flood magnitude of 24,50,000 cusecs gets attenuated to 5,42,407 cusecs for NWDT award, while it gets attenuated to 11,00,840 for modified NWDT award.

CHAPTER 1

INTRODUCTION

1.1. General

Water is an essential basic resource which is necessary for the existence of all life form. It is required in abundance to meet irrigation, domestic and industrial, etc., needs. Its availability is restricted in terms of quantity, quality, time and space or combination of these factors.

The water resource systems are complex hence assumptions are made to simplify it. The complexity of the problem may be due to the complicated inter-relationship between various components of the system, data limitations, uncertain hydrology, demand pattern, etc.

The design of a water resource system consists of (i) determination of physical size to yield certain target outputs and (ii) establishment of an optimal operating policy. This involves the interaction of political, legal, governmental, economic and engineering processes. In the development of any river basin, generally, the first priority is given to irrigation. The water requirements for power generation, domestic and industrial purpose are given second choice. The reason is that there is no other substitute available for the irrigation water, while power may be generated by the use of coal, oil, nuclear energy. It is observed that large habitations developed first in the delta reaches of the river basin because of easy availability of water in large quantities.

System analysis is used to search out 'best' solution in terms of objective functions by joining engineering and economic aspects together. The data required for analyzing water resource problems include hydrologic and hydrometeorological records, cost and benefit functions, economic loss functions and demand patterns. In general benefits cannot be estimated with absolute reliability.

The system components and their interrelationships are first identified. An idealized representation of the system is made through a mathematical model by making simplifications and assumptions. Care must be taken to see that the model is still a valid representation of the problem during the process of simplifying the system. An objective function is a very important part of mathematical model. It is described by a mathematical expression. It quantifies the effects of alternative courses of action in the system model.

All possible short-comings, errors or oversights in the model should be identified in advance before its results are implemented. Data requirements should be scrutinized for compatibility with data availability. Solution for the model will only be an approximation to the solution of the real world problem.

1.2. Optimization Techniques Commonly Used

It is essential that river basin model and selected optimization technique are compatible. The linear programming (LP) and dynamic programming (DP) or a joint use of these two

are the commonly used optimization techniques for solving the water resource problems. Their uses are restricted to preliminary screening. DP has limited use if there are many state variables in each stage. Its use is limited due to the so called "curse of dimensionality" (Bellman, et al., 1962).

Simulation model is used to evaluate the performance of various configuration of reservoirs, power plant capacity, water use allocation and operating policies, for given hydrological inputs.

Optimization model is designed to select the best plan out of many alternatives for a specific objective. Simulation model is better suited for the detailed analysis of specific alternative. The final design and operating policies is selected on the basis of results of these studies.

1.3. Present Study

The aim of the present research study is to determine optimal operation of five serially linked reservoirs located on the main stem of the river Narmada using optimization-simulation technique. Discontinuous linear programming model (LPD) with deterministic inflows is used to arrive at design variables such as reservoir size, installed capacity of power house and seasonal water releases for irrigation and power for each reservoir. Further screening is done by using the steepest ascent method. A set of design variables which produces maximum net benefit is selected for the use of simulation study. A simulation computer program developed by HEC:

"Reservoir yield" is modified and used to test the efficiency and performance of the system for specified operating policies.

Simulation study requires a long record of streamflows. Historical record of streamflows are too short to include all possible pattern of drought and floods. Generation of synthetic streamflows provides longer sequences. Streamflow data are generated using technique of stochastic hydrology.

A monthly streamflow simulation computer program has been developed by Hydrologic Engineering Centre (HEC-4). The monthly streamflow data are generated for a desired length using this program and with available record of historical streamflows as input data. A number of simulation studies are carried out using historical streamflows and synthetic streamflows as input data. The other input data are: design parameters, release policies, and maximum and minimum permissible storage in each period and for each reservoir.

1.4. Organisation of Report

Chapter 2 consists of various methods and techniques available and their limitations to analyze water resource systems. Chapter 3 deals with various techniques of generation of synthetic streamflows. Chapter 4 consists of the use of LPD model for preliminary screening. Chapter 5 includes the use of the steepest ascent method for further screening of design variables. The description of simulation program is given in Chapter 5. The results obtained from LPD model, steepest ascent method and simulation studies are described in Chapter 6. In

the same chapter discussion of results are included. Summary and recommendations for further studies are given in Chapter 7.

1.5. Units Used in the Present Study

In order to keep the study as close to a real problem as possible, actual data from published literature, and from the report of the Narmada Water Disputes Tribunal (NWDT), Volumes I to IV are used. These data are generally in FPS system and hence the same units are retained in this study.

CHAPTER 2

REVIEW OF LITERATURE

2.1. Introduction

Mathematical programming and simulation techniques have been applied to water resource systems, during last few decades. Research has progressed from analysis of a single reservoir to a system of multireservoirs, encompassing an entire river basin. Harvard Water Group did pioneering work to study the basic principles, concepts and methodology for designing and planning of water resource systems.

A combination of linear programming, simulation and response surface methods was used by the Texas Water Development Board (TWDB). Their aim was to seek 'near optimum' solution rather than exact optima. The procedures adopted by them are as under:

1. The components of the system and operating rules are determined by an optimization method.
2. Initial screening is carried out by using the method of random sampling.
3. A gradient search is used to reduce further range of variables.
4. The most attractive schedules are improved by successive perturbations.
5. A pattern search (Hooks and Jeeves, 1961) is used to reach the optimum in the vicinity of the crevices (Himmelblau, 1974).

2.2. Available Analytical Techniques for Study of Water Resource Systems

2.2.1. Linear programming

Linear programming is widely used in water resource systems. Manne (1962) has shown that the problem of infinite planning horizon can be solved by using linear programming with the assumption that the objective function and constraints are a linear function of decision variables. Thomas and Watermeyer (1962) used the linear programming formulation of Manne for sequential decision model. Their main objective was to determine the optimal draft rate for each period and optimal capacity of reservoir to maximize the benefits. Their decision regarding releases is based on the initial storage and random inflows during that period.

There are two types of linear programming models namely linear programming continuous (LPC) and linear programming discontinuous (LPD). LPC obeys the continuity law for one or more periods while LPD violates the continuity law for one or more periods. Loucks (1981) advocates the use of both models. Dorfman (1962) illustrated the use of mathematical programming techniques, especially, linear programming and a special type of nonlinear programming, namely separable programming, for solving water resource systems. Martinez (1971) used deterministic LPD for solving a single multipurpose reservoir. Rogers (1969) used a linear programming formulation for the lower Ganges and Brahmaputra rivers in India and Bangladesh. He considered seven reservoir sites in India and a single site in Bangladesh. The objective function includes benefits due to power and

irrigation, cost of surface and ground water storages, and cost of embankments, all reduced to annual costs.

2.2.2. Chance constrained programming

One of the techniques used to take into account the stochastic nature of inflow is the chance constrained programming technique. This method was developed by Charnes and Cooper (1958).

The linear decision rule (LDR) was first developed by Revelle, et al. (1969). He applied this technique for finding out optimal capacity and operating rules for a single reservoir using stochastic inflows. Revelle and Kirby (1970), Joeres, et al. (1971), Nayak, et al. (1971, 1974), Estman, et al. (1973), LeClerc, et al. (1973) and Revelle and Gundelach (1975) have modified, extended, and/or applied this method to reservoir management problems. Eisel (1972), Loueks (1970), Sobel (1974), have pointed out the drawbacks of linear decision rules. Loueks and Dorfman (1975) recommended that these rules may be used for initial screening study, as they are conservative for design purpose. Lane (1973), Askew (1974) have used this method in their study. Houeks and Datta (1981) developed multiple LDR model. It is superior to single LDR model for equivalent restrictions on reservoir operation and performance. The multiple LDR model gives a smaller capacity reservoir than a single LDR model.

Dantzing and Wolfe decomposition principle can be used to reduce modeling effort as well as to save computer time, when the system is very large. In case of nonlinear objective

function and a few nonlinear constraints, a piecewise linearization technique is found suitable. The problem becomes complicated and unmanageable as the number of nonlinear constraints increases.

2.2.3. Nonlinear programming

Nonlinear programming techniques are not commonly used for the analysis of water resource systems. Few authors who have used this technique are Chu and Yeh (1978), Himmelblau (1977), and Bayer (1974). Bayer used nonlinear programming in river basin water quality model. He compared his results with the results obtained by other researchers using linear and dynamic programming to solve river basin water quality optimization problems. Himmelblau used two nonlinear programming techniques; (i) a Generalised Reduced Gradient (ii) a Conjugate Gradient Projection method in his water quality model.

2.2.4. Dynamic programming

There is vast literature available for DP technique used by many researchers. This technique was used by them in their study of a single multipurpose reservoir. The reasons were (i) dimensionality of the problem was well within the realm of the computer memory and (ii) nonlinear objective function. Little (1955) used DP for optimizing the operation of a hydropower system. Buras (1963) used DP for solving conjuctive operation of a reservoir-ground water system. Hall and his associates (1961, 1964, 1966, 1968) proposed a number of DP formulations to analyze a multipurpose reservoir system.

Their aim was to find optimal schedule of releases such that the maximum benefits are obtained from the sale of water for irrigation and for power. Young (1967) combined deterministic DP and hydrologic simulation to determine the optimal draft from a single reservoir. Mobasheri, et al. (1970) used modified DP for determining an optimal long term operating policy for a single reservoir. Parikh (1966) used DP for a single reservoir with a deterministic hydrology and used a decomposition principle of linear programming. Meir and Brighter (1967) used DP in their study to optimize a multistage water resource systems. Schwing and Cole (1968) used DP to study the optimal control of linked reservoirs. Lieu and Tedrow (1973) used DP in their study of a multilake river system to find operating rules. Harley and Chidley (1978) used deterministic DP to determine long term reservoir operating policies for a reservoir system. Collins (1977), and Opricobic, et al. (1976) used DP in their study to find optimal long term control of a multipurpose reservoir. Bhaskar, et al. (1980) used DP for deriving monthly reservoir release policy.

2.2.5. Stochastic dynamic programming

The stochastic nature of inflows are taken into account in dynamic programming by using stochastic dynamic programming. Few authors who have used this technique are Butcher (1971), Dudley and Burt (1973), Su and Deininger (1974), Mawer and Thorn (1974) and Torabi and Mobasheri (1973).

Torabi and Mobasheri used stochastic dynamic programming for determining the optimal operating policy of a single

multipurpose reservoir. They developed a dynamic programming model with a physical equation and a stochastic recursion equation for deriving the optimum operating policy. Butcher used this technique for a multipurpose single reservoir. In his study, the optimal operating policy is stated in terms of the state of the reservoir (storage volume) and riverflow in the preceding month.

2.2.6. Incremental dynamic programming with successive approximations

This method has been used by Troat and Yeh (1973) and Nopmongcol and Askew (1976). Troat and Yeh used this method to determine the optimal design of a system of reservoirs with series and parallel connections. The return from the system is determined for an optimal operating policy and a specified set of reservoir sizes. This policy is determined by decomposing the original problem by Bellman's method of successive approximations. The multistage problem is decomposed into a series of subproblems of one state variable. A sequence of optimization over the subproblems converges to the solution of the original problem. The costs are assumed to be a function of reservoir size and are computed from storage capacity versus cost curves. A modified gradient technique is used to determine the set of reservoir sizes which maximizes the net benefits with the imposed constraints. Nopmongcol and Askew developed a multilevel incremental dynamic programming. The basic concept is directly dependent on certain characteristics of incremental dynamic programming (IDP). They found marked reduction in

computing time by using this technique. It increases the power of IDP. It can be used as a tool in the optimization of multi-dimensional deterministic systems.

2.2.7. Incremental dynamic programming

State increment dynamic programming technique was introduced by Larson (1968). A different version of an increment concept for state variable has been used by Hall, et al. (1969) and is known as incremental dynamic programming. The major difference between them is the nature of the time interval used in computation. Time interval is a variable in the former while it is fixed in the latter.

2.2.8. Multiobjective dynamic programming (MODP)

This has been used by Tauxi, et al. (1981) They developed mathematical models for determining release policies that maximize dump energy and minimize cumulative evaporation. The major characteristics and advantages of MODP are as under:

(a) Noncommensurable objective functions can be handled quantitatively.
(b) The entire noninferior solution set is available from one solution of the problem.
(c) Trade-off ratio are available explicitly between objectives.

2.2.9. Markov models

A discrete probability distribution concept is used in Markov model. The following two approximations are made to

describe the probability distribution of streamflows, reservoir volumes, and other hydrologic events.

(a) The discrete probabilities can be approximated by continuous probabilities.

(b) Discrete interval of time can be approximated by continuous time interval.

Many other approximations are also necessary in addition to the above, to preserve mathematical tractability and essence of an actual water resource system (Shen, 1976). Gablinger, et al. (1970) used Morkov model for flow regulation.

2.2.10. Monte Carlo technique

Monte Carlo analysis is valid for sequential decision processes. It is used to test the policy, using equally likely sequences (Hall and Dracup, 1975). Askew, et al. (1970) used Monte Carlo technique in the design and operation of multipurpose reservoir system.

2.2.11. Queuing theory

This can be applied to the problem of selecting the optimal design of a single multipurpose reservoir. Langbein (1958) used this technique to find reservoir capacity, by maintaining a minimum regulated draft, provided that inflow is normally distributed and draft is a linear function of storage. Gani and Moran (1955) have given the outline for using queuing theory and Monte Carlo analysis. Thomas, et al. (1982) gave an elagant queuing theory solution for selecting the optimal scale of development and optimal operating policy for a single

multipurpose reservoir. Fiering (1961) applied this technique associated with Monte Carlo method to study the optimal size of a single multipurpose reservoir using an economic efficiency objective.

Mathematical programming technique has been extensively used by many researchers for planning and designing the water resource system and for finding operating policies. There is no general algorithm. The choice of the technique depends mostly on the characteristic of reservoir system, availability of data, objective and constraints.

2.3. Limitations of Optimization Models

The optimization model is unable to give exact solution to the problem due to following limitations.

(1) Many assumptions are made to simplify the real problem in order to make the problem solvable. The objective function (cost and benefit function), energy production function, evaporation function, flood damage function, loss function, etc., are generally nonlinear. One has to take recourse to nonlinear programming technique in such situations which takes lot of computer time and thus proves to be costly. Nonlinear programming problems have no general algorithms for solution. To overcome this, linearization may have to be done.

(2) The second limitation is more conceptual. It stems from inability to fix a criterion for evaluating each possible management alternative with regard to quantifications.

(3) The third is nonavailability of reliable and compatible data. Hence the optimization models are restricted to preliminary screening designs (Biswas, 1976).

Stochastic optimization model contains more variables and constraints than that of deterministic model of the same system. It requires huge computer memory, hence it is restricted to small subbasins. Houck, et al. (1978) used stochastic linear programming model for design and management of multipurpose reservoir system.

2.4. Simulation Models

Simulation model is capable of evaluating the hydrological and economic performance of a large scale river basin. Ackoff (1961) defines simulation as a process which "duplicates the essence of the system or activity without actually attaining reality itself". Naylor (1973) defines simulation as a "numerical technique for conducting experiments with certain types of mathematical models which describe the behaviour of a complex system on a digital computer over extended periods of time". He states further that "the principle difference between simulation experiments and real world experiments is that with simulation the experiments are conducted with a model of real system rather than with the actual system itself".

Six major phases of a simulation have been listed by Churchman, Ackoff and Arnoff (1957): (i) formulation of problem, (ii) constructing mathematical model to represent the system under study (iii) deriving solution from the study (iv) testing the model and solution derived from it (v) establishing control

over the solution and (vi) putting the solution to work (implementation). Simulation model takes into account nonlinear, dynamic, and stochastic responses of the system.

2.5. Optimization-Simulation Technique

Considering the complexity and inherent characteristics of a reservoir system, a joint use of optimization and simulation technique is found more suitable. Beeker and Yeh (1974) used this technique for their study of operation of multi-reservoir system. Jacoby and Loueks (1972) used analytical and optimization models to screen the set of design variable worthy for simulation analysis. The combination of LP and stochastic DP was developed by Takeuchi and Moreau (1974). Roefs and Bodin (1970) classified optimization into two approaches, the explicit stochastic optimization (ESO) and implicit stochastic optimization (ISO). The ESO uses the probability distribution of inflows instead of inflow sequences. In the ISO, the generated inflow sequences and deterministic optimization method are used to determine optimal releases. Hirsch, et al. (1977) studied the gains from the joint operation of multi-reservoir system. Hufschmidt and Fiering (1966) carried out systematic study of a system of reservoirs by simulation. Fredrich and Beard (1972) used simulation to analyze the water resources problem including (i) determination of the specified set of projects to be constructed, (ii) timing of construction and (iii) method of operation, so as to minimize the sum of capital and operation cost over the planning period.

Reservoir zoning concept was given by Beard (1967). According to this concept, each reservoir is divided into a number of storage zones and during simulation all reservoirs are maintained in the same zone as far as possible. Operating policies are based on priority concept or some prescribed inter-reservoir relationship. A generalised simulation program for the operation of reservoir system for conservation purposes such as water supply, recreation, low flow augmentation, and hydroelectric power was developed by Hydrologic Engineering Centre, U.S. Army of Corps of Engineers (HEC-3, 1974).

Ford and Fulkerson (1962), Durbin and Kroenke (1967) developed a new approach to simulate a complex water resource system using out-of-kilter algorithm (OKA) to a network of reservoirs. A system can be represented by a series of nodes and arcs in a 'capacitated network' form analogous to an electric circuit. Texas Water Development Board (TWDB) developed a number of computer programs (TWDB-1, 1970; TWDB-2, 1972; TWDB-3, 1972) using this technique. Sigvaldason (1976) used the concept of reservoir zoning and OKA to simulate the operation of a multipurpose and multireservoir system.

2.6. Streamflow Generation Techniques

Simulation study requires a long seqence of streamflows. In most of the river basins of India, the historical records are not long enough to make predictions about mean, high and low flows. Hence it is not possible to assess reliable performance of the water resource system. A long sequence of flow data

is generated using technique of stochastic hydrology, preserving the important statistical parameters of historical flow data.

After testing the system with possible alternative sequence of hydrologic input data, the planner may be able to formulate effectively and efficiently the development proposals. "Synthetic flows do not improve poor records but merely improve the quality of design made with whatever records are available" (Fiering and Jackson, 1971). A design based only on short historical sequences may lead to under or over design to an unknown extent.

The data generating models can be classified into two groups- short memory models, and long memory models. Markov, and ARIMA (Auto-regressive-integrated moving average) models belong to the short memory group, while Fractional Gaussian Noise (FGN), and Broken Line (BL) processes belong to the long memory group. The term memory is used as a synonym for persistence. It means a tendency for high flows to follow high flows and low flows to follow low flows at a station. The short memory models have been criticized for their inability to simulate a relatively high value of Hurst coefficient (around 0.7) observed in long historical record. Long memory models have been developed to take care of Hurst coefficient (Singh,1979). Fiering (1967) and Fiering and Jackson (1971) summarised the use of short memory processes. Mandelbrot and Wallis (1969).and Matalas and Wallies (1971) have considered long term hydrologic persistence in generating synthetic flow sequences using FGN.

FGN model is found to be expensive. Lettenmair and Burges (1977) have proposed a mixed ARIMA-Markov model.

2.7. Time Series Components of Streamflow:

Four components are associated with stream flow (Kottegoda, 1970): trend T_t, periodic SE_t, correlation C_t, and random ε_t. If they are combined together by an additive model then the expression becomes $X_t = T_t + SE_t + C_t + \varepsilon_t$. A time series is a sequence of values arranged in order of their occurrence. It is stationary if the statistical properties are time invariant. The monthly data can be standardized by the following equation;

$$X_t' = \frac{X_t - X_j}{S_j} \qquad (2.1)$$

where,

X_t = monthly flows;

X_t' = standardized monthly flows;

X_j = mean flow for the jth month.

In general, it is found that annual flows obey normal distribution, while the monthly flows obey Log-normal distribution. Markov or an auto-regressive (AR) model of order p can be written as,

$$X_t = \varepsilon_t + \sum_{i=1}^{p} \emptyset_i X_{t-i} \qquad (2.2)$$

where,

X_t = AR process at time t;

ϕ_i = AR parameters; $i = 1, 2, \cdots\cdots p$

ε_t = random component, $t = 1, 2, \cdots\cdots 12$

The Lag-one Markov model has been widely used in generation of annual flows, using the equation

$$X_t = \phi_1 X_{t-1} + (1 - \phi_1)^{1/2} \varepsilon_t \tag{2.2a}$$

Persistence is one of the characteristics of time series. It can be calculated in term of serial correlation. Lag-one serial correlation is serial correlation between an event and the immediately preceding event. Kottegoda (1970) has reported that Lag-one models are quite reliable.

2.8. Synthetic Streamflow Generation Techniques

2.8.1. Short memory models

The Russian mathematician Markov introduced the concept of Markov process. The probability distribution of any trial depends directly on the preceding trial. The following Markov model is proposed by Brittan to represent actual stream flows;

$$X_{i+1} = \underbrace{\bar{X} + \gamma(X_i - \bar{X})}_{\text{deterministic}} + \underbrace{t_i S (1 - \gamma^2)^{1/2}}_{\text{random}} \tag{2.3}$$

where,

X_{i+1}, X_i = annual runoff for (i+1)th and ith years;

$\bar{X}$ = mean annual historical flows;

γ = annual Lag-one serial correlation coefficients;

t_i = normal random variate of zero mean and unit variance (McMohan and Mein, 1978).

Thomas and Fiering (1962) developed the following algorithm:

$$X_{i+1} = \overline{X}_{j+1} + b_j(X_i - \overline{X}_j) + t_i\, S_{j+1}\, (1 - \gamma^2)^{1/2} \tag{2.4}$$

where,

X_{i+1}, X_i = generated flows during the (i+1)th, ith seasons;

$\overline{X}_{j+1}$, $\overline{X}_j$ = mean flows during (j+1)th, jth seasons;

b_j = least square regression coefficient for estimating (j+1)th flows from the jth flows and

$$b_j = \gamma_j \frac{S_{j+1}}{S_j} ;$$

t_i = normal random variate with zero mean and unit variance;

S_{j+1}, S_j = standard deviation of flows during the (j+1)th, jth seasons.

Thomas and Burden (1963) transformed the normal variate t_i to a skewed variate t_r with an approximate Gamma distribution, using Wilson and Hilferty transformation to take care of skewness in data:

$$t_r = \frac{2}{\nu_{t,j}} \left[1 + \frac{\nu_{t,j}\, t_i}{6} - \frac{\nu_{t,j}^2}{36}\right]^3 - \frac{2}{\nu_{t,j}} \tag{2.5}$$

where,

$\nu_{t,j}$ = co-efficient of skewness of "like Gamma" variate;

t_i = N(0, 1);

t_r = G(0, 1, $t_{r,j}$);

j = repetetive annual cycle of season.

McMohan and Miller (1971) reported that the Wilson and Hilferty transformation failed in case of large skewness. Matalas (1967)

presented moment transformation equations. The main assumption made is that logarithms of flows follow normal distribution. The algorithms for estimation of parameters for three parameter lognormal model are as follows;

$$x_{i+1} = \bar{x}_{j+1} + B_j(x_i - \bar{x}_j) + t_i \, s_{j+1}(1 - R_j^2)^{1/2} \tag{2.6}$$

$$\bar{x}_j = A_j + \exp(0.5\, s_j^2 + \bar{x}_j) \tag{2.7}$$

$$s_j^2 = \exp\,[2(s_j^2 + \bar{x}_j)] - \exp(s_j^2 + 2\bar{x}_j) \tag{2.8}$$

$$g_j = \frac{\exp\,[3s_j^2] - 3\,\exp(s_j^2) + 2}{[\exp(s_j^2) - 1]^{3/2}} \tag{2.9}$$

$$\gamma_j = \frac{\exp\,[s_j \cdot s_{j+1}\;R_j] - 1}{[\exp(s_j^2) - 1]^{1/2}\,[\exp(s_{j+1}^2) - 1]^{1/2}} \tag{2.10}$$

$$B_j = R_j\left[\frac{s_{j+1}}{s_j}\right] \tag{2.11}$$

Moreau and Pratt (1970) generated weekly flows with the assumption that weekly flows obey lognormal distribution. A moving average process is used to reduce sampling errors, i.e., smoothening of raw data. They developed a nonstationary model for synthesizing weekly flows such that means and variances of weekly and monthly flow will be preserved. A scheme for generating daily flows at a single station has been developed by Quimpo (1968). Yevjevich (1966) used the concepts of stationary time series and Fourier analysis to produce sequences at a single site. Young and Pisano (1968) developed an operational

model based on a combination of the model suggested by Matalas and transformation studied by Yevjevich.

2.8.2. Long memory models

(i) Fractional Gaussian Noise (FGN): Mondelbrot and Wallis (1969) introduced the Fractional Gaussian Noise (FGN) model to take care of large value of Hurst's coefficient, say $h > 0.5$. Approximations are necessary to compute FGN variate which involves an infinite number of operations. They have used type 1 and type 2 approximations. Type 1 approximation is expensive with respect to computer time. Type 2 approximation is deficient in high frequencies. Low frequency approximation is satisfactory when h is close to one. Matalas and Wallis (1971) proposed a filtering technique to account for high frequency behaviour of type 2 approximation. The drawback is that it takes large amount of computer time. Mandelbrot (1972) developed Fast Fractional Gaussian Noise (FFGN) to overcome the difficulty met with FGN.

(ii) Broken Line models (BL): Mejia, et al. (1972) presented a long term memory model, namely, Broken Line (BL) model. It is a continuous time process which produces Hurst effect, Lag-one correlation of flows, and the second derivative of correlation function at the origin. The second derivative is related to crossing properties of streamflow function. Lawerence and Kottegoda (1972) have defined the second derivative as the number of times the flow rate crosses a given level and the

expected time between such crossings. This model has several defects. It is slightly non-Gaussian and is unable to produce actual crossing properties. The definition of crossing properties is not well defined.

CHAPTER 3

STREAMFLOW GENERATION MODEL

3.1. Introduction

The present study deals with studies relating to the optimal development of the Narmada river basin. This basin will have several reservoirs for meeting demands of irrigation, power, etc. The historical record of streamflows at a few stations on the river is not very long. Hence there is a need to generate streamflows by using streamflow generation techniques.

It is a simple procedure to generate synthetic flow sequences at a single site. It becomes cumbersome when more sites are included. It is desirable that the data generating technique must preserve important statistical parameters of the historical flows at stations and at the same time be able to generate compatible flow data.

It is a major problem, with the generating models used for multisites, to preserve cross correlation among various sites. A number of models are available for generation of monthly streamflows for multisite situation. Looking at the limitation of computer time, it has been decided to use 'HEC-4: monthly streamflow simulation model' developed by Hydrologic Engineering Centre, U.S. Army Corps of Engineers, for the Narmada river basin under study. It has been found that in general, annual flows obey normal distribution, while monthly flows obey lognormal distribution.

3.2. HEC-4 Model

3.2.1. Model options

The HEC-4 model has the following options (Reference HEC-4 Manual).

(a) Analyze monthly streamflow at a number of interrelated stations (up to 10 stations can be analyzed simultaneously) to determine their statistical characteristics.

(b) Fill-in missing flows and test for consistency of matrices of correlation coefficients.

(c) Generate a sequence of hypothetical streamflows of any desired length, having statistics obtained in item (a).

(d) Obtain maximum, minimum and averages of recorded, reconstituted and generated flows for each month and for specified duration.

The model can be used for other purposes such as rainfall, evaporation and demands.

3.2.2. Computational steps

(a) Increment the monthly flows at each station by 1% of average flow of the corresponding month. The incrementing of historical data is to avoid possibility of negative logarithms while transforming the flow data into logarithmic form in the initial stage of computation. The increment q_i is substracted from the generated sequences in the final stage of computations.

(b) The mean, standard deviation and skew coefficient for each station and for each month are computed using the following equations:

$$X_{i,j} = \log (Q_{i,j} + q_i) \tag{3.1}$$

$$\bar{X}_i = \sum_{j=1}^{N} X_{i,j}/N \tag{3.2}$$

$$S_i = \sqrt{\sum_{j=1}^{N} (X_{i,j} - \bar{X}_i)^2/(N-1)}\ . \tag{3.3}$$

$$g_i = N \sum_{j=1}^{N} (X_{i,j} - \bar{X}_i)^3/[(N - 1)(N - 2)S_i^3]\ . \tag{3.4}$$

where,

X = logarithm of incremented monthly flow;

Q = monthly recorded flow;

q = small increment of flow used to prevent infinite logarithm for month of zero flow;

$\bar{X}$ = mean logarithms of incremented monthly flows;

N = total years of record;

S = unbiased estimate of population standard deviate;

g = unbiased estimate of population skew coefficient;

i = subscript used for month;

j = subscript used for year.

(c) Using the above derived statistical parameters, historical flow data are first transformed to Pearson type III standard deviate and then to normal standard deviate.

Transformation to Pearson type III deviate 't' is performed by;

$$t_{i,j} = (X_{i,j} - \overline{X}_i)/S_i \tag{3.5}$$

(d) Transformation of Pearson type III deviate 't' to normal standard deviate 'K' is performed by;

$$K_{i,j} = \frac{6}{g_i}\left[(g_i\, t_{i,j}/2 + 1)^{1/3} - 1\right] + g_i/6 \tag{3.6}$$

(e) After transforming the flows for all months in respect of all stations to normal deviates, the simple correlation coefficient 'R' between all pairs of stations, for each current and preceding month are computed by using the formula;

$$R_i^2 = \left[1 - \left\{1 - \left(\sum_{j=1}^{N} x_{i,j}\, x_{i-1,j}\right)^2 \Big/ \left(\sum_{j=1}^{N} x_{i,j}^2 \sum_{j=1}^{N} x_{i-1,j}^2\right)\right\} (N - 1)/(N-2)\right] \tag{3.7}$$

in which $x = X - \overline{X}$.

(f) If the sets of historical record are not completed for all stations, first phase of computation involves completion of all sets maintaining consistency of all correlation matrices. When the sets of flows are complete, generation of hypothetical stream flow is accomplished.

The serial and cross-correlation coefficients (correlation matrices) form the basis of relationship between dependent variable (relating to the missing month or month to

be constituted) and the independent variables (for stations having flows for that month already generated and other stations with flows of the antecedent month). The regression equation from the above relations are then computed for each station and month by Crout method.

(g) The regression equation is of the form;

$$K'_{i,n} = \beta_1 K'_{i,1} + \beta_2 K'_{i,2} + \beta_3 K_{i,3} + \dots + \beta_{n-1} K'_{i,n-1}$$
$$+ \beta_n K'_{i-1,n} + \beta_{n+1} K'_{i-1,n+1} + \dots +$$
$$\beta_m K'_{n-1,m} + Z_{i,n}(1 - R^2_{i,n})^{1/2} \qquad (3.8)$$

where,

K' = monthly flow logarithm expressed as a normal standard deviate;

β = beta coefficient computed from correlation matrix;

i = subscript used for month;

n = subscript used for station;

m = number of interrelated stations;

R = multiple correlation coefficient;

Z = random number from standard normal population.

(h) By the above formula the normal standard deviates are computed for each station in turn for one month at a time. The process is started with average values (zero deviation) for all stations in the first month.

(i) Normal standard variates are then converted to flows by back transformation using the following equations;

$$t_{i,j} = \left[\left\{ (g_i/6)(K'_{i,j} - g_i/6) + 1 \right\}^3 - 1 \right] \times \frac{2}{g_i} \tag{3.9}$$

$$X_{i,j} = \overline{X}_i + t_{i,j}\, S_i \tag{3.10}$$

and

$$Q_{i,j} = - q_i + \text{Antilog}\ X_{i,j} \tag{3.11}$$

For incomplete records the following measures are taken:

(j) For each station and month with incomplete record, say station 1, a search is made among all the stations to find a station, say station 2, which has a longer record and good correlation with station 1. The length of equivalent record (N_1') to be used from station 2 to correct the statistics of station 1 is given by;

$$N_1' = \frac{N_1}{1 - \left(\frac{N_2' - N_1}{N_2'}\right) R^2} \tag{3.12}$$

(k) Using this equivalent length of record of station 2 and corresponding statistics, the statistics of station 1 are corrected by;

$$\overline{X}_1' - \overline{X}_1 = (\overline{X}_2' - \overline{X}_2)\ R\ S_1/S_2' \tag{3.13}$$

$$S_1' - S_1 = (S_2' - S_2)\ R^2\ S_1/S_2' \tag{3.14}$$

The primes indicate the long period values and without prime are based on the same short period for both stations 1 and 2.

(l) When incomplete records or gaps are encountered the correlation coefficients computed in step (e) are not complete. The missing values of correlation coefficients are estimated by the equation;

$$R_{in} = R_{ki} R_{kn} \pm \sqrt{(1 - R_{ki}^2)(1 - R_{kn}^2)} \qquad (3.15)$$

In order to be consistent with the two related correlation coefficients, the correlation coefficient must lie between the limits given by equation (3.15). These are established for all related pairs, and the average of these two limits is taken as the estimated correlation coefficient.

(m) All the correlation matrices are tested for their consistency (determination coefficients should be less than one). The test of consistency for each complete matrix is made by recomputing the multiple correlation coefficient. If this value is greater than one, an adjustment is made by introducing a coefficient, successively smaller by 0.2, on the radical in equation (3.15). All trial consistency tests are repeated until all matrices become consistent.

3.3. Streamflow Gauging Sites of the Narmada River

The Narmada river basin extends over an area 38,114 square miles and lies between east longitude 72°-32' to 81°-45' and north latitude 21°-20' to 23°-45'. Lying in the Northern extremity of the Deccan plateau, the basin covers

large areas in the States of Madhya Pradesh and Gujarat and comparatively smaller area in Maharashtra. The State-wise distribution of the drainage area is as under:

State	Drainage area in square miles
Madhya Pradesh	33,123
Maharashtra	593
Gujarat	4,398
Total	38,114

The basin is bounded on the north by the Vindhyas, on the east by Maikala range, on the south by Satpuras and on the west by the Arabian sea. The basin has an elongated shape as shown in Figure 3.3, with a maximum length of 592 miles from east to west and a maximum width 145 miles from north to south. The basin is divided into three zones namely upper zone, middle zone and lower zone. The upper zone extends from source to Bargi dam, middle zone from Bargi dam to Narmadasagar and the lower zone from Narmadasagar to Sardar Sarovar.

The Narmada river is the fifth largest river in India. The total length of river from the head to its outfall in the sea is 815 miles. The river has 41 tributaries, out of which 22 are on the left bank and 19 on the right bank. There are only three main gauging sites on the main stream namely Jamtara, Mortakka and Garudeshwar. Daily discharge observations

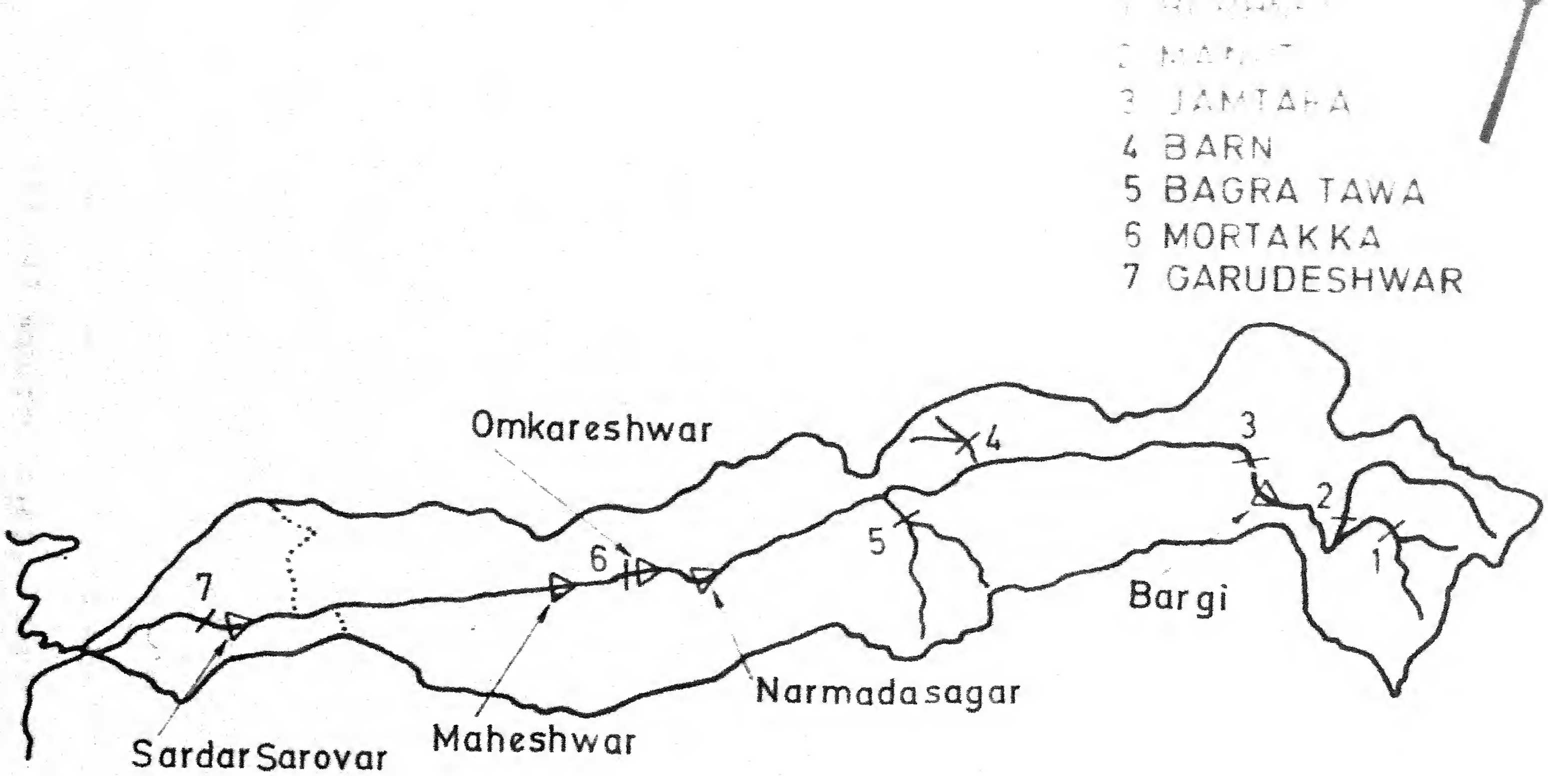


FIG. 3.3 DISCHARGE SITES AND MAJOR RESERVOIRS ON THE NARMADA RIVER SYSTEM

are taken at each gauging site. Monthly discharge data are available for 28 years at each gauging site.

There are 30 major projects proposed for the whole basin. Out of these, five are purely hydropower projects while others are multipurpose projects. Five major projects to be developed on the main stem of the river Narmada are: Bargi, Narmadasagar, Omkareshwar, Maheshwar and Sardar Sarovar.

3.4. Streamflow Data

As already stated there are three gauging sites along the main stem of the river Narmada. Jamtara is situated 12 miles below Bargi dam site. It is at a distance of 247 miles from source. It covers a catchment area of 6400 square miles. Observations are carried out daily with current meter. During rainy season, observations are taken from a bridge on the South Eastern Railway line from Balaghat to Jabalpur. During dry weather, the site is shifted 1000 ft downstream where the water flows through a narrow channel. Observations from 1948 are available. Monthly streamflow data are tabulated in Table 3.4.1.

The Mortakka gauging site is situated 37 miles below Narmadasagar dam site. It is located at a distance of 562 miles from the source. The catchment area up to this gauge site is 25,942 square miles. Daily discharge readings are taken with floats at a section 3000 ft downstream of a Railway bridge on the Western Railway from Khandwa to Indore. Observations from 1948 are available. The monthly streamflow data are tabulated in Table 3.4.2.

TABLE 3.4.1. STREAMFLOW AT JAMTARA GAUGE SITE
(Flows in cfs)

Water year	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	March	April	May	June
1948-49	30250	58531	38652	5399	3546	1382	894	918	537	168	49	403
1949-50	9725	31973	22620	100C2	2302	748	651	738	846	370	81	353
1950-51	37877	59117	18587	2261	756	651	520	360	179	773	114	555
1951-52	1480	34576	17763	5025	807	472	228	162	98	50	16	1798
1952-53	30315	59296	32031	3366	992	520	520	360	114	34	16	17
1953-54	24281	39146	16688	3204	1008	537	325	162	65	50	16	286
1954-55	17028	28932	37140	4668	1227	439	358	306	130	50	16	6890
1955-56	18394	48139	53390	18849	3344	1269	602	378	163	101	49	2454
1956-57	57588	87984	22368	10311	4386	1399	1464	594	781	487	114	218
1957-58	26070	53034	20351	2911	924	472	293	216	390	118	16	67
1958-59	30298	27891	25158	17174	2891	992	781	666	179	118	49	50
1959-60	39438	60808	44349	8050	1916	927	1025	522	309	286	81	1328
1960-61	22167	56905	13545	11368	2000	976	732	756	276	84	16	3731
1961-62	77169	68923	73506	14084	3378	1968	1090	702	472	286	114	1193
1962-63	11449	29599	25359	3871	1311	4521	829	360	228	134	130	1832
1963-64	14442	39357	41492	3724	1613	797	504	396	244	84	33	1025
1964-65	40658	69379	24485	7253	1765	927	602	414	228	387	49	1613
1965-66	6408	8457	16268	1643	555	309	276	180	65	17	16	3529
1966-67	16263	34429	4487	846	370	342	211	144	504	437	65	1563
1967-68	39129	77169	40366	5269	1412	2000	2862	1170	634	168	98	857
1968-69	17434	46171	9445	3009	1008	585	488	180	98	50	16	34
1969-70	22329	71493	19813	3350	1378	634	569	306	699	134	114	3781
1970-71	18459	47017	7882	5416	2790	960	618	594	423	235	211	16805
1971-72	56206	37763	38820	15743	9159	976	699	414	244	151	65	101
1972-73	5074	53604	27225	2992	1445	1090	569	144	211	101	16	134
1973-74	29209	60239	42181	21240	2370	1269	1138	576	260	118	49	403
1974-75	6831	47098	3479	2358	555	472	342	270	195	84	16	134
1975-76	22004	37096	25662	13124	2252	1220	764	576	211	168	81	118

Note: The monthly flows shown are average discharge rates during the month.

(Flows in cfs)

Water year	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	March	April	May	June
1948-49	124788	186653	189766	34413	22385	10555	6229	4826	3529	2235	1464	4100
1949-50	61784	110541	187917	52449	17041	6798	4082	3151	3578	2386	1773	2134
1950-51	117485	149882	113671	16279	5798	4586	4359	3097	2342	3983	1756	4016
1951-52	24606	98002	63255	16036	5966	3562	2814	2593	1773	1160	846	6319
1952-53	61296	178619	68734	11498	4958	3334	2879	2719	1789	1176	781	1042
1953-54	68614	192995	60314	13450	5445	3513	2765	2143	1269	992	764	1882
1954-55	45342	83349	212906	36917	11949	5773	3692	2791	1447	1008	748	8083
1955-56	33551	147442	263003	96847	16738	7595	4846	3565	2358	1781	1301	13041
1956-57	164405	199615	77674	40300	25964	9254	7985	5258	4277	4201	2017	7092
1957-58	44740	132659	78346	12832	6084	3854	3057	2467	2326	1361	960	3042
1958-59	60418	107662	139047	58808	17309	6765	4245	3385	2244	1428	992	2353
1959-60	152468	226920	225141	46545	14318	7140	7237	4465	3171	2218	1675	4571
1960-61	76827	231263	44551	35242	10571	6798	4651	3961	2651	1916	1382	8588
1961-62	142612	167853	362255	92977	20234	10474	7400	5492	4066	3227	1952	1512
1962-63	43455	76535	174775	22801	9411	10604	5090	3547	2765	1765	1171	3580
1963-64	26363	136855	140392	21061	7747	4944	3415	2773	2244	1512	1122	5697
1964-65	91806	206819	84430	31112	9024	5025	3675	2485	1789	1647	960	2403
1965-66	41016	29469	53357	7562	2840	2017	1740	1440	929	689	602	739
1966-67	49782	109858	37812	4960	2706	2261	1594	1224	911	1512	585	4840
1967-68	56824	159379	139434	19012	5798	7188	5806	3241	2732	1361	862	1059
1968-69	53847	211975	58130	17613	5546	3578	2814	1927	1382	958	634	790
1969-70	77120	278345	113553	20849	7882	4505	4033	3061	2830	1546	1041	24015
1970-71	74713	156696	270112	25224	8369	5155	3838	3187	2456	1647	1561	36131
1971-72	142368	111679	152088	61768	12066	6424	4700	3637	2895	1630	1317	4067
1972-73	39764	201127	155500	15661	6756	4830	2992	3997	2033	1412	829	1580
1973-74	239427	276035	257844	58043	13730	7530	4846	4087	2976	2033	1496	2891
1974-75	27322	221993	25494	16686	7378	4326	3123	2953	2439	1597	699	9697
1975-76	69200	217309	172187	45000	17192	9904	6505	4033	1773	2201	1626	2924

Note: The monthly flows shown are average discharge rates during the month.

The Garudeshwar gauging site is situated 7 miles below Sardar Sarovar. It is located at a distance of 730 miles from the source. It covers a catchment area of 34,496 square miles. From 1948 to 1961, daily discharge observations were made by float method with the help of a boat plying across the river. In April 1961, a high level bridge was completed across the river for the Eastern State highway and the discharge observations are taken with current meter. Observations made with float have been correlated subsequently with the observations made with current meter. The monthly streamflow data are tabulated in Table 3.4.3. For 3-hourly flood routing study, four floods namely floods of 1959 (September), 1961 (September), 1970 (September) and 1975 (September) are selected as standard floods observed at Mortakka and Garudeshwar gauging sites. The daily discharge data for these floods are tabulated in Tables 3.4.4 to 3.4.7.

The monthly as well as annual statistical parameters like mean and standard deviation of the observed historical streamflow records at each gauging site are tabulated in Tables 3.4.8 and 3.4.9. The maximum and minimum values are also shown in the same tables.

In the present study, five reservoirs namely Bargi, Narmadasagar, Omkareshwar, Maheshwar and Sardar Sarovar are considered. The Bargi dam site is situated at a distance of 235 miles from the source. The catchment area up to Bargi is 6090 square miles. The Jamtara is the nearest gauging site. The streamflow data observed at Jamtara are transferred on the basis of drainage area ratio.

TABLE 3.4.3. STREAMFLOW DATA AT GARUDESHWAR SITE
(Flows in cfs)

Water year	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	March	April	May	June
1948-49	138660	218838	248752	38040	23981	12360	6879	4537	3383	2319	1350	6857
1949-50	64353	121551	237812	83463	22267	8815	4180	4645	3724	2521	1643	2017
1950-51	116461	177220	181917	30412	10789	6489	6017	3385	2521	2470	1691	3781
1951-52	43569	116981	66599	16312	6168	4456	3236	2665	1854	1126	585	6588
1952-53	56954	182994	74817	13173	6117	3806	3009	2539	1643	941	537	8554
1953-54	60987	208429	67641	18475	6537	4489	3610	1999	1334	823	520	2504
1954-55	61020	87285	305319	16312	19629	9205	6001	4285	1415	992	683	11142
1955-56	39682	143572	309436	115518	19393	9205	6749	5636	3610	2403	1659	14772
1956-57	163949	232190	76313	40593	22469	8132	7839	5834	4505	4218	1952	10554
1957-58	42317	152809	85203	16621	7814	5123	4163	3025	2521	1580	976	3966
1958-59	68322	113013	179565	68745	9293	3383	2114	1566	1025	639	358	992
1959-60	115225	278166	336459	68501	29561	14751	13027	9831	6310	4353	3301	11512
1960-61	62922	239215	51340	85024	8705	5204	4196	3997	3497	2454	1220	7294
1961-62	154029	193630	457172	154874	23813	9351	5871	4591	3171	2353	1594	1428
1962-63	50790	83024	217797	25159	9142	9481	4293	2845	2261	1597	1138	8016
1963-64	25273	153053	156222	18654	8167	4359	4326	3853	1952	1714	1220	5882
1964-65	87122	209340	95286	37357	8806	5529	5351	3151	1968	1479	1203	2302
1965-66	42040	41374	63356	9010	2706	1887	1545	1278	878	555	390	471
1966-67	42821	129715	58600	6570	2958	2261	1756	1386	1025	1462	651	9041
1967-68	80389	182831	181531	22443	8638	9026	6700	3817	3301	1529	911	1294
1968-69	33079	290396	71507	23256	8957	5448	3285	2323	1887	1412	732	1664
1969-70	83105	339348	186287	21321	9394	4960	4391	3871	2814	2050	1008	60348
1970-71	82129	147865	370977	40983	12873	6700	4521	3493	2553	1933	1545	46500
1971-72	151394	121616	175515	63882	14738	7416	5123	3385	2423	1512	1334	3798
1972-73	50107	211080	164464	19174	10134	7026	2033	4465	2326	1815	1171	3832
1973-74	284720	248209	389782	76405	19696	8863	5464	4213	3253	2151	1854	2991
1974-75	32526	246225	33779	23582	10587	6017	3741	3115	2309	1496	1106	9982
1975-76	68761	273368	212638	39308	15293	7367	4944	3349	2326	1865	1610	30589

Note: The monthly flows shown are average discharge rates during the month.

TABLE 3.4.4. AVERAGE DAILY DISCHARGE FOR SEPTEMBER 1959 FLOOD (Flows in cfs)

Date	Name of gauging sites	
	Mortakka	Garudeshwar
1	287907	494377
2	184372	407793
3	814865	283674
4	334715	978000
5	278235	601528
6	245229	418529
7	261855	408532
8	143000	307856
9	161956	278964
10	289742	229000
11	414175	380527
12	380710	590560
13	265844	463728
14	303368	355350
15	971385	1175890
16	255537	759816
17	180277	327511
18	145930	307714
19	112007	247921
20	94886	199169
21	80978	144484
22	73671	131700
23	66364	120776
24	61140	93271
25	57892	98765
26	52350	80121
27	47373	60698
28	47478	80800
29	52597	69649
30	52279	75904
sum	6718117	10111750
Average monthly flow	13.325 MAF	20.0516 MAF

TABLE 3.4.5. AVERAGE DAILY DISCHARGE FOR SEPTEMBER 1961 FLOOD (Flows in cfs)

Date	Name of gauging sites	
	Mortakka	Garudeshwar
1	167216	122300
2	140247	181075
3	124538	183559
4	241276	128870
5	386112	154409
6	367932	505373
7	281906	510105
8	194856	410570
9	630459	283130
10	1191380	1189166
11	888854	1376788
12	405103	916681
13	209859	425313
14	137670	299027
15	111760	214393
16	998213	169560
17	1191020	1445455
18	862344	1410000
19	237181	520642
20	177277	292592
21	177277	238289
22	137882	218179
23	118396	173610
24	111760	158225
25	137211	124669
26	184266	231367
27	314876	521724
28	317418	545235
29	153520	380210
30	175335	282740
Sum	10773143	13739178
Average monthly flow	21.368 MAF	27.245 MAF

TABLE 3.4.6. AVERAGE DAILY DISCHARGE FOR SEPTEMBER 1970 FLOOD (Flows in cfs)

Date	Name of gauging	
	Mortakka	Garudeshwar
1	369244	278941
2	398813	370650
3	437141	373474
4	1055901	540090
5	1097028	1242913
6	1366240	2153300
7	812125	2252140
8	354049	360160
9	200322	508320
10	161061	367120
11	134173	223802
12	118336	68482
13	183143	153555
14	161208	218860
15	128634	190832
16	104578	148260
17	84265	127080
18	76535	113172
19	68982	104629
20	61114	93439
21	52658	78401
22	51565	66964
23	82303	91074
24	84265	78366
25	80924	104135
26	80924	102370
27	119984	103429
28	79583	114372
29	59274	101664
30	53198	75189
sum	8117570	11131027
Average monthly flow	16.100 MAF	22.075 MAF

TABLE 3.4.7. AVERAGE DAILY DISCHARGE FOR SEPTEMBER 1975 FLOOD (Flows in cfs)

Date	Name of gauging sites	
	Mortakka	Garudeshwar
1	124397	169864
2	155779	169652
3	171381	262350
4	161992	264503
5	222108	208552
6	177382	312758
7	157579	236828
8	136399	208446
9	136823	169758
10	155955	180277
11	328537	369979
12	211870	840271
13	1029350	1189610
14	611750	430413
15	272304	297050
16	168698	214800
17	131563	156061
18	102546	132234
19	88285	91590
20	76035	77766
21	67600	64281
22	60998	56586
23	59339	50479
24	61316	52986
25	76601	60504
26	61916	75274
27	59339	61493
28	56091	52279
29	57433	46772
30	64600	48114
sum	5309143	6377803
Average monthly flow	10.134 MAF	12.653 MAF

TABLE 3.4.8. STATISTICS OF STREAMFLOWS AT THREE GAUGE SITES (Flows in cfs)

Gauge site No. and name	Month	Flow max	Flow min	Flow mean	Standard deviation	75% dependable flow
	July	77169	1480	25999	17335	
	Aug	87984	8457	49076	17585	
	Sept	73506	3479	27254	15663	
	Oct	21240	846	7375	5726	
	Nov	9159	370	2052	1731	
11	Dec	4521	309	1031	813	
Jamtara	Jan	2862	211	713	815	
	Feb	1170	144	449	256	
	March	846	65	314	219	
	April	773	17	187	171	
	May	211	16	61	48	
	June	16805	17	1831	3335	
Annual statistics		242885	37723	116341	44906	81749 (4.95 MAF)
	July	239427	24606	78998	51068	
	Aug	278345	29469	164555	60629	
	Sept	362255	25494	140060	84255	
	Oct	96847	4960	33284	23792	
	Nov	25964	2706	10757	6105	
12	Dec	10604	2017	6010	2496	
Mortakka	Jan	7985	1594	4300	1648	
	Feb	5492	1224	3268	1029	
	March	4277	911	2392	860	
	April	4201	689	1807	829	
	May	2017	585	1176	432	
	June	36131	739	6007	7597	
Annual statistics		870938	142398	452613	167573	354130 (21.43 MAF)

Note: The monthly and annual flows are average discharge rates.

TABLE 3.4.9. STATISTICS OF STREAMFLOWS AT THREE GAUGE SITES
(Flows in cfs)

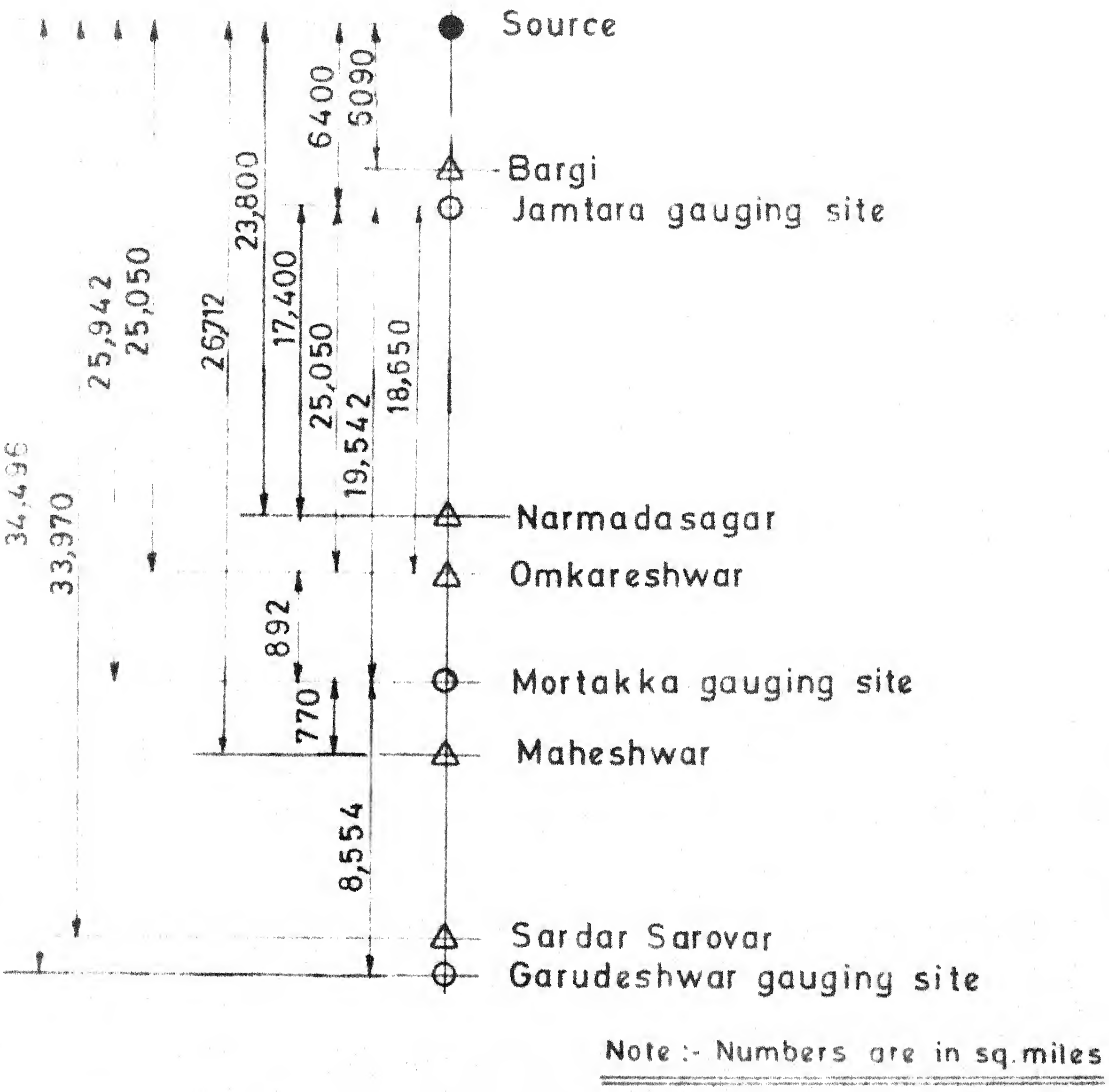
Gauge site No. and name	Month	Flow max	Flow min	Flow mean	Standard deviation	75% dependable flow
13 Garude-shwar	July	284720	25273	82240	55750	
	Aug	339348	41374	183691	70456	
	Sept	467172	33779	180503	116684	
	Oct	154874	6570	42613	35229	
	Nov	29561	2706	12808	7069	
	Dec	14751	1887	6825	2920	
	Jan	13027	1545	4799	2283	
	Feb	9831	1278	3681	1664	
	March	6310	878	2564	1162	
	April	4353	555	1849	887	
	May	3301	358	1212	613	
	June	60348	471	9952	13798	
Annual statistics		1047601	165490	532737	213372	379180 (22.94 MAF)

Note: The monthly and annual flows are average discharge rates.

Narmadasagar is located at a distance of 525 miles from the source. The catchment area up to Narmadasagar is 23,800 square miles. The nearest gauging site is Mortakka. The inflow series between Jamtara and Mortakka are determined. The streamflows are transferred to Narmadasagar and Omkareshwar dam sites on the basis of drainage area ratio. A schematic sketch as shown in Figure 3.4.1 shows the location of gauging sites, dam sites and drainage areas covered by them.

Omkareshwar site is 34 miles below Narmadasagar i.e. 559 miles from the source. The catchment area up to Omkareshwar dam site is 25,050 square miles. The nearest gauging site is Mortakka. Maheshwar is located at a distance of 585 miles from the source. It is 23 miles below Mortakka gauge site. The catchment area up to Maheshwar is 26,712 square miles. The inflow series between Mortakka and Garudeshwar gauging sites are evaluated. The streamflows are transferred to Maheshwar and Sardar Sarovar dam sites on the basis of drainage area ratio. The transferred streamflows data at each dam site are tabulated in Tables 3.4.10 to 3.4.14. The maximum, minimum, mean and standard deviation for each month are computed at each dam site for 28 years of record of streamflows and tabulated in Tables 3.4.15 to 3.4.17.

It is found that the time lag observed between the peaks of flood observed at Mortakka and Garudeshwar is 12 hours. A travel time of 15 hours is assumed between Narmadasagar and Sardar Sarovar. The flood hydrographs for four selected floods observed at Mortakka and Garudeshwar gauge sites are plotted



3.4.1 SCHEMATIC SKETCH OF DAM SITES, GAUGING SITES AND DRAINAGE AREAS

TABLE 3.4.10. STREAMFLOW DATA AT BARGI AS TRANSFERRED FROM JAMTARA GAUGE SITE (Flows in cfs)

Water year	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	March	April	May	June
1948-49	28785	55696	36780	5137	3374	1315	851	874	511	160	47	383
1949-50	9254	30424	21524	9518	2190	712	619	702	805	352	77	336
1950-51	36042	56254	17687	2151	719	619	495	343	170	736	108	528
1951-52	1408	32901	16903	4782	768	449	217	154	93	48	15	1711
1952-53	28847	56424	30479	3203	944	495	495	343	108	32	15	16
1953-54	23105	37250	15880	3049	959	511	309	154	62	48	15	272
1954-55	16203	27531	35341	4442	1168	418	341	291	124	48	15	6556
1955-56	17503	45807	50804	17936	3182	1208	573	360	155	95	47	2335
1956-57	54799	83722	21285	9812	4174	1331	1393	565	743	463	108	207
1957-58	24807	50465	19366	2770	879	449	279	206	371	112	15	64
1958-59	28830	26540	23939	16342	2751	944	743	634	170	112	47	48
1959-60	37528	57863	42201	7660	1823	882	975	497	294	272	77	1264
1960-61	21093	54149	12889	10817	1903	929	697	719	263	80	15	3550
1961-62	73431	65585	69946	13402	3214	1873	1037	668	449	272	108	1135
1962-63	10894	28165	24131	3683	1247	4302	789	343	217	128	124	1743
1963-64	13742	37451	39482	3544	1535	758	480	377	232	80	31	975
1964-65	38689	66018	23299	6902	1680	882	573	394	217	368	47	1535
1965-66	6098	8047	15480	1563	528	294	263	171	62	16	15	3358
1966-67	15475	32761	4270	805	352	325	201	137	480	416	62	1487
1967-68	37234	73431	38411	5014	1344	1903	2723	1113	603	160	93	815
1968-69	16590	36986	8988	2863	959	557	464	171	93	88	15	32
1969-70	21247	68030	18853	3188	1311	603	541	291	665	128	108	3598
1970-71	17565	44740	54018	5154	2655	914	588	565	403	224	201	15991
1971-72	53484	35934	36940	14980	8716	929	665	394	232	144	62	96
1972-73	4828	51009	25906	2847	1376	1037	541	137	201	96	15	128
1973-74	27794	57321	40138	20211	2255	1208	1083	548	247	142	47	383
1974-75	6500	44817	3310	2244	528	449	325	257	186	80	15	128
1975-76	20938	35299	24419	12488	2143	1161	727	548	201	160	77	112

Note: The monthly flows shown are average discharge rates during the month.

TABLE 3.4.11. INFLOW BETWEEN BARGI AND NARMADASAGAR BASED ON OBSERVED FLOWS AT JAMTARA AND MORTAKKA GAUGING SITES
(Flows in cfs)

Water year	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	March	April	May	June
1948-49	85641	116914	136423	26095	16946	8234	4794	3524	2690	1849	1262	3311
1949-50	86824	71504	148274	38279	13235	5423	3086	2184	2474	1813	1510	1603
1950-51	72717	83680	85562	12591	4526	3535	3443	2454	1935	2896	1468	3109
1951-52	20663	58149	41366	10047	4633	2774	2314	2172	1496	991	740	4113
1952-53	29054	109116	34231	7404	3579	2531	2126	2118	1497	1018	682	913
1953-54	40650	138882	39652	9278	3999	2676	2188	1772	1075	841	667	1435
1954-55	26035	49854	158299	28940	9606	4771	2986	2227	1179	855	653	1396
1955-56	14387	90750	189223	70362	12088	5694	3808	2856	1962	1501	1117	9545
1956-57	97898	103657	50327	27201	19425	7062	5877	4182	3151	3330	1700	6131
1957-58	17886	73466	52624	8975	4639	3034	2475	2015	1743	1112	841	2652
1958-59	28286	72378	102624	37902	12978	5188	3122	2453	1847	1172	842	2053
1959-60	102551	150850	163124	34665	11135	5577	5581	3536	2563	1734	1423	2952
1960-61	49742	158003	28264	21808	7728	5231	3525	2890	2128	1635	1217	4505
1961-62	62008	91425	260660	70928	15172	7669	5671	4299	3223	2632	1642	342
1962-63	29052	43225	134267	17043	7276	5635	3834	2855	2270	1459	933	1645
1963-64	11314	88818	90069	15617	5540	3731	2616	2136	1793	1276	971	4210
1964-65	47511	125736	54560	21595	6549	3694	2765	1864	1401	1141	814	782
1965-66	31125	19119	33812	5350	2061	1536	1317	1131	771	599	523	0
1966-67	30633	68829	29890	3704	2098	1725	1242	969	387	978	466	2994
1967-68	17651	76937	90164	12492	3974	4716	2760	1901	1899	1070	685	221
1968-69	33226	156015	43806	13149	4089	2693	2095	1564	1148	811	551	675
1969-70	49867	187642	84425	15743	5858	3477	3112	2468	1931	1264	831	18199
1970-71	50982	99934	192709	17899	5103	3782	2897	2338	1831	1269	1212	18022
1971-72	79440	67643	102733	41743	3032	4898	3596	2890	2372	1324	1118	3536
1972-73	31130	133949	115523	11425	4799	3383	2185	3438	1633	1172	725	1294
1973-74	188591	195060	194067	33798	10230	5636	3357	3154	2431	1711	1291	2235
1974-75	18576	158006	19770	12872	6102	3454	2493	2402	2007	1351	600	8521
1975-76	43089	162257	131707	29018	13412	7791	5149	3106	1401	1818	1380	2504

Note: The monthly flows shown are average discharge rates during the month.

TABLE 3.4.12. INFLOW BETWEEN NARMADASAGAR AND OMKARESHWAR BASED ON OBSERVED FLOWS AT JAMTARA AND MORTAKKA GAUGING SITES
(Flows in cfs)

Water year	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	March	April	May	June
1948-49	6047	8195	9666	1855	1205	587	341	250	191	132	91	236
1949-50	3330	5026	10573	2715	943	387	219	154	175	129	108	114
1950-51	5092	5806	6082	897	323	252	246	175	138	205	105	221
1951-52	1479	4057	2910	704	330	198	165	155	107	71	53	289
1952-53	1982	7632	2348	520	254	180	151	151	107	73	49	66
1953-54	2836	9841	2791	655	284	190	156	127	77	60	48	102
1954-55	1811	3481	11243	2063	686	341	213	159	84	61	47	76
1955-56	970	6352	13408	4989	857	405	271	204	140	107	80	677
1956-57	6833	7140	3538	1918	1380	502	417	298	224	238	122	440
1957-58	1194	5093	3710	635	330	216	177	144	124	80	60	190
1958-59	1927	5103	7285	2663	922	369	222	174	132	84	60	147
1959-60	7230	10625	11564	2462	793	397	397	252	183	124	102	207
1960-61	3496	11153	1983	1527	548	372	251	205	152	117	87	311
1961-62	4186	6328	18470	5046	1078	544	404	306	230	188	118	20
1962-63	2047	3002	9557	1211	518	389	273	204	162	104	67	112
1963-64	763	6236	6326	1109	392	265	186	152	128	91	70	299
1964-65	3272	8791	3834	1526	464	262	197	132	100	81	58	51
1965-66	2214	1344	2372	379	146	109	94	81	55	43	37	0
1966-67	2144	4825	2132	263	149	123	88	69	26	69	33	210
1967-68	1132	5259	6337	879	281	332	188	132	134	76	49	13
1968-69	2329	11073	3114	934	290	191	149	112	82	58	40	48
1969-70	3505	13231	5996	1119	416	248	222	176	136	90	59	1294
1970-71	3598	7016	13647	1267	357	268	206	166	130	90	86	1236
1971-72	5511	4728	7245	2944	186	348	256	206	170	95	80	254
1972-73	2219	9436	8205	810	340	239	155	246	117	84	52	92
1973-74	13447	13803	13795	2354	727	400	237	225	174	122	93	159
1974-75	1311	11187	1408	916	436	247	178	172	144	97	44	612
1975-76	3019	11527	9372	2039	956	555	367	221	100	130	99	179

Note: The monthly flows shown are average discharge rates during the month.

TABLE 3.4.13. INFLOW BETWEEN OMKARESHWAR AND MAHESHWAR BASED ON OBSERVED FLOWS AT MORTAKKA AND GARUDESHWAR GAUGING SITES
(Flows in cfs)

Water year	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	March	April	May	June
1948-49	5564	8746	12207	1651	1004	581	302	152	123	102	54	417
1949-50	2607	4577	12036	4729	1143	458	165	245	138	104	66	71
1950-51	3542	6604	10483	1912	679	351	324	151	115	10	69	137
1951-52	2763	4604	2378	527	254	222	156	117	84	48	14	231
1952-53	1023	5840	2043	522	285	171	119	91	63	31	13	723
1953-54	1337	8412	2651	920	301	224	187	77	61	28	12	129
1954-55	2704	2838	16342	0	1181	552	360	248	57	42	28	330
1955-56	1244	4184	13748	5241	850	434	365	332	213	133	89	639
1956-57	4835	8028	2402	1395	670	258	285	265	180	171	81	625
1957-58	634	5448	3264	794	391	269	226	153	106	76	45	219
1958-59	2086	4123	8846	2795	0	0	0	0	0	0	0	0
1959-60	1807	12195	18273	3734	1938	969	805	663	413	280	219	773
1960-61	1243	8674	2026	5571	223	122	138	150	185	132	48	105
1961-62	4015	6836	21724	9173	1092	287	150	138	83	56	52	7
1962-63	2121	2727	10693	1076	346	177	123	82	70	59	45	479
1963-64	446	5908	5939	575	318	137	215	206	65	83	59	230
1964-65	1913	6500	3713	1651	312	232	291	154	87	42	63	27
1965-66	1672	2031	2593	401	92	66	49	43	35	19	8	0
1966-67	903	5230	3392	333	129	88	78	64	29	45	30	528
1967-68	2929	5864	8311	936	456	402	215	146	147	70	39	30
1968-69	0	14961	3426	1175	514	305	149	115	104	82	37	113
1969-70	3040	14933	10826	841	433	218	190	199	96	110	39	4194
1970-71	3235	4211	18818	2323	660	331	208	146	102	90	60	1816
1971-72	4745	4268	7279	2291	373	338	221	124	79	57	59	157
1972-73	2514	7630	6663	895	546	368	24	218	110	96	63	269
1973-74	13673	7345	21721	3333	1056	406	225	172	149	98	98	123
1974-75	1404	10164	1751	1275	600	328	183	137	91	60	68	462
1975-76	2115	13272	10329	943	511	168	122	96	121	63	69	2617

Note: The monthly flows shown are average discharge rates during the month.

TABLE 3.4.14. INFLOW BETWEEN MAHESHWAR AND SARDAR SAROVAR BASED ON OBSERVED FLOWS AT MORTAKKA AND GARUDESHWAR GAUGING SITES
(Flows in cfs)

Water year	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	March	April	May	June
1948-49	11770	27309	50049	3077	1354	1532	552	0	0	71	0	2339
1949-50	2180	9342	42336	26315	4434	1711	83	1268	124	115	0	0
1950-51	0	23196	57906	11992	4235	1615	1407	244	152	0	0	0
1951-52	16090	16104	2837	234	171	759	358	61	69	0	0	228
1952-53	0	3712	3464	1421	983	400	110	0	0	0	0	6374
1953-54	0	13096	6217	4264	927	828	717	0	55	0	0	528
1954-55	13303	3340	78412	0	6516	2912	1959	1268	0	0	0	2596
1955-56	5202	0	39398	15842	2253	1366	1615	1757	1062	528	304	1469
1956-57	0	27640	0	249	0	0	0	489	193	14	0	2937
1957-58	0	17097	5818	3215	1468	1077	938	473	165	185	14	784
1958-59	6706	4540	34379	8431	0	0	0	0	0	0	0	0
1959-60	0	43482	94452	18629	12934	6458	4913	4553	2663	1812	1380	5889
1960-61	0	6747	5760	42240	0	0	0	31	718	456	0	0
1961-62	9687	21872	80536	52519	3037	0	0	0	0	0	0	0
1962-63	6224	5506	36504	2001	0	0	0	0	0	0	0	3764
1963-64	0	13744	13432	0	356	0	773	916	0	171	83	157
1964-65	0	2139	9211	5299	0	428	1422	565	152	0	206	0
1965-66	869	10101	8484	1229	0	0	0	0	0	0	0	0
1966-67	0	16849	17638	1366	214	0	137	137	97	0	56	3565
1967-68	19995	19899	35719	2911	2410	1560	759	489	483	143	42	199
1968-69	0	66540	11350	4788	2894	1587	400	336	428	385	83	742
1969-70	5078	51761	61714	400	1283	386	304	687	0	428	0	30828
1970-71	6292	0	85583	13371	3822	1311	580	260	82	243	0	8798
1971-72	7658	8431	19878	1794	2267	842	359	0	0	0	14	0
1972-73	8776	8445	7614	2981	2866	1863	0	397	249	342	290	1911
1973-74	38431	0	111948	15580	5062	1131	524	107	235	100	304	85
1974-75	4416	20561	7030	3581	2723	1435	524	137	0	0	345	242
1975-76	0	47566	34322	0	0	0	0	0	469	0	0	23457

Note: The monthly flows shown are average discharge rates during the month.

TABLE 3.4.15. STATISTICS OF TRANSFERRED STREAMFLOWS
(Flows in cfs)

Station No. and name	Month	Flow max	Flow min	Flow mean	Standard deviation	75% dependable flow
	July	73431	1408	24740	16496	
	Aug	83722	8047	46699	16733	
	Sept	69946	3310	27595	15360	
	Oct	20211	805	7018	5449	
	Nov	8715	352	1953	1648	
101 Bargi	Dec	4302	294	981	774	
	Jan	2723	201	678	490	
	Feb	1113	137	427	243	
	March	805	62	298	208	
	April	736	16	178	163	
	May	201	15	58	46	
	June	15991	16	1742	3173	
Annual statistics		231120	35895	112367	43061	77788 (4.71 MAF)
	July	188591	11314	48449	37082	
	Aug	195060	19119	105198	45035	
	Sept	260660	19770	100292	63115	
	Oct	70928	3704	23426	17103	
	Nov	19425	2061	7850	4750	
102 Narmada-sagar	Dec	8234	1536	4484	1793	
	Jan	5877	1242	3229	1231	
	Feb	4299	969	2534	807	
	March	3223	387	1866	657	
	April	3330	599	1451	631	
	May	1700	466	995	362	
	June	18199	221	3920	4591	
Annual statistics		641561	98195	303694	120933	230034 (13.92 MAF)

Note: The monthly and annual flows are average discharge rates.

TABLE 3.4.16. STATISTICS OF TRANSFERRED STREAMFLOWS

(Flows in cfs)

Station No. and name	Month	Flow max	Flow min	Flow mean	Standard deviation	75% dependable flow
103 Omkare-shwar	July	93447	763	3390	2638	
	Aug	13803	1344	7387	3205	
	Sept	18470	1408	7104	4486	
	Oct	5046	263	1657	1213	
	Nov	1380	146	557	339	
	Dec	587	109	318	127	
	Jan	417	88	230	88	
	Feb	306	69	180	58	
	March	230	26	133	47	
	April	238	43	104	45	
	May	122	33	71	26	
	June	1294	13	276	322	
Annual statistics		45536	6933	21406	8583	16201 (0.980 MAF)
104 Omkare-shwar	July	13447	763	2718	2541	
	Aug	13803	1344	6994	3443	
	Sept	18470	1408	8710	6295	
	Oct	5046	263	2036	2051	
	Nov	1380	146	584	421	
	Dec	587	109	302	191	
	Jan	417	88	210	149	
	Feb	306	69	167	120	
	March	230	26	111	76	
	April	238	43	78	56	
	May	122	33	55	41	
	June	1294	13	480	818	
Annual statistics		48399	7009	22446	10501	14501 (0.877 MAF)

Note: The monthly and annual flows are average discharge rates.

TABLE 3.4.17. STATISTICS OF TRANSFERRED STREAMFLOWS (Flows in cfs)

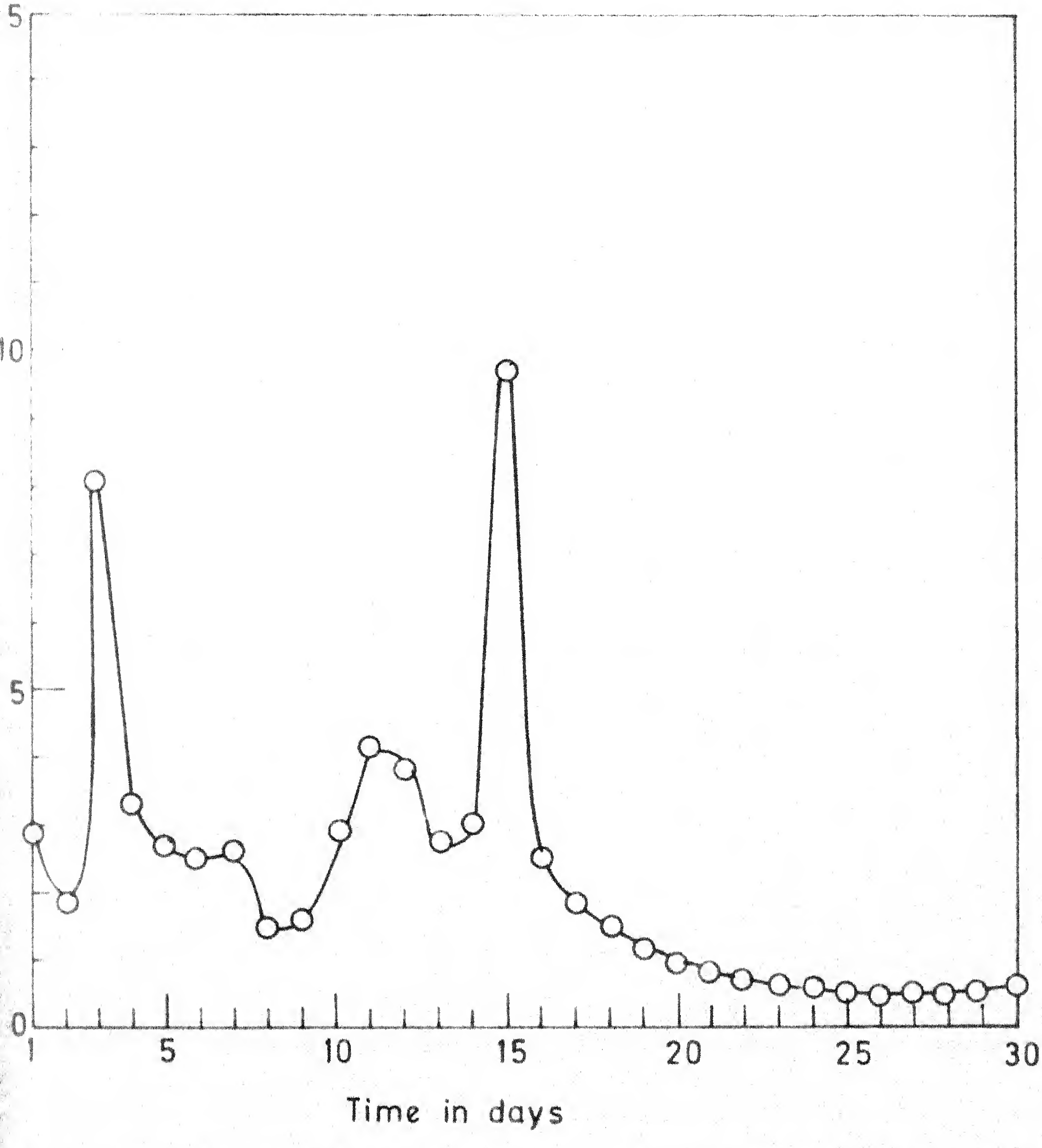
Station No. and name	Month	Flow max	Flow min	Flow mean	Standard deviation	75% dependable flow
105 Sardar Sarovar	July	281835	25340	82037	55346	
	Aug	335597	40642	182514	69689	
	Sept	451335	33270	178016	114594	
	Oct	151068	6471	42039	34411	
	Nov	28624	2714	12682	6945	
	Dec	14283	1898	6775	2854	
	Jan	12671	1557	4768	2221	
	Feb	9501	1288	3656	1605	
	March	6117	881	2553	1132	
	April	4222	563	1846	872	
	May	3201	397	1210	596	
	June	58114	487	9709	13344	
Annual statistics		1036638	164069	527806	210408	377640 (22.85 MAF)

Note: The monthly and annual flows are average discharge rates.

using daily discharge data and they are shown in Figures 3.4.2 to 3.4.9. The 3-hourly flood ordinates are obtained and tabulated in Tables 3.4.18 to 3.4.25.

The flood ordinates are moved forward in time 3-hours for Narmadasagar. They are modified on the basis of mean monthly flow ratio. For Omkareshwar, the travel time between Omkareshwar and Mortakka is small and hence no travel time is allowed. The ordinates are however moderated on the basis of mean monthly flow ratio. For Maheshwar the flood ordinates are first lagged by 3-hours and they are moderated on the basis of mean monthly flows ratio. For Sardar Sarovar, the travel time between Sardar Sarovar and Garudeshwar is assumed as zero. The flood ordinates are however modified on the basis of the mean monthly flows ratio.

The 75% dependable flow at Sardar Sarovar is 27.0 MAF which is decided on the basis of the record of annual flows of 79 years. They are tabulated in Table 3.4.26. It is mentioned in the NWDT Volume 3 that the 75% dependable flow at Mortakka and Garudeshwar gauging sites is 22.0 MAF and 27.22 MAF respectively on the basis of 79 years. It is found that with 28 years of record, the 75% dependable flow at Jamtara, Mortakka and Garudeshwar gauging sites is 4.95 MAF, 21.43 MAF, and 22.94 MAF respectively. It is mentioned in the NWDT Volume 1 that with 22 years of record the 75% dependable flow at Jamtara, Mortakka and Garudeshwar gauging sites is 5.15 MAF, 20.30 MAF, and, 22.60 MAF respectively.



4.2 FLOOD HYDROGRAPH AT MORTAKKA (SEPT. 1959)

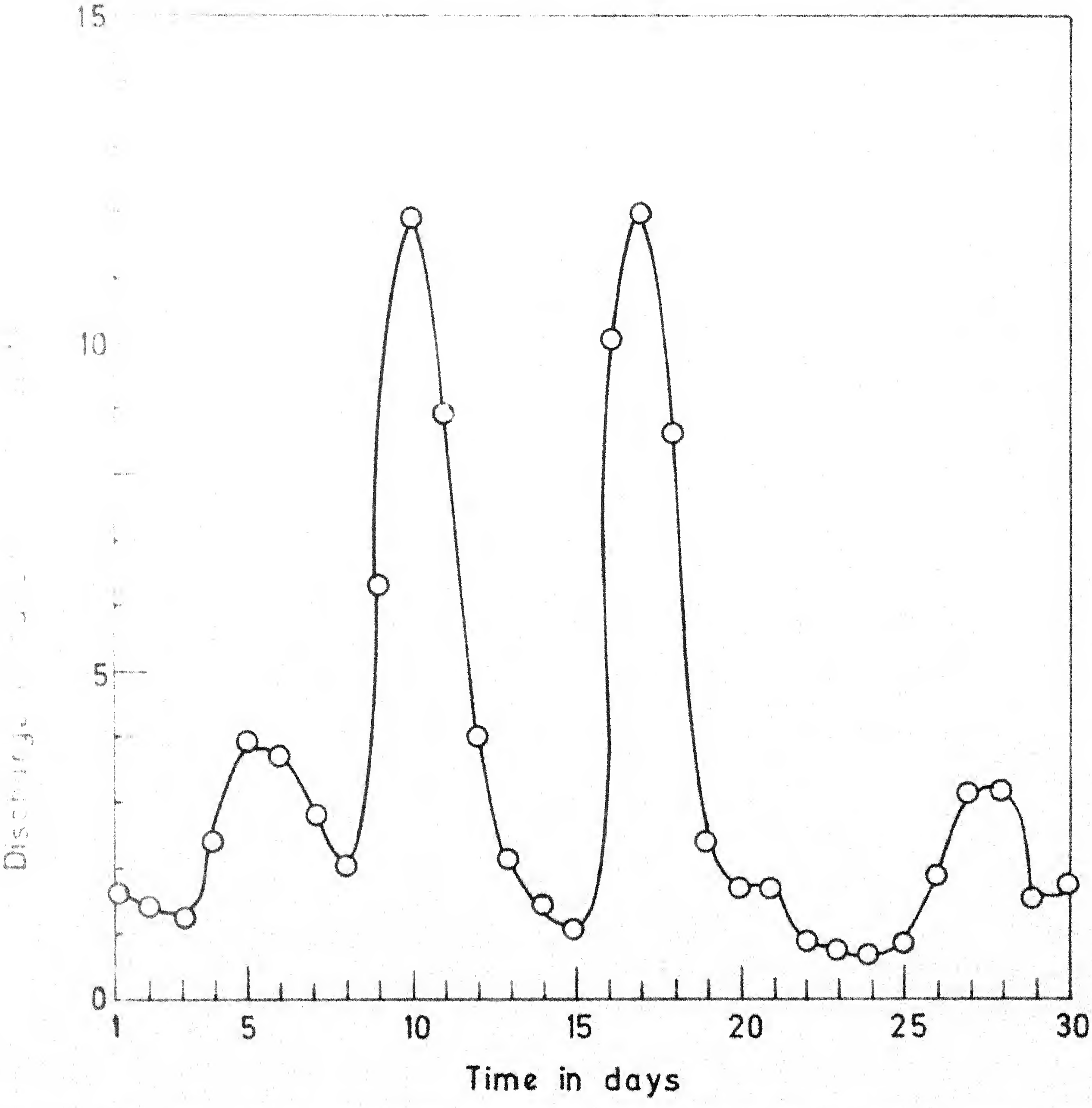
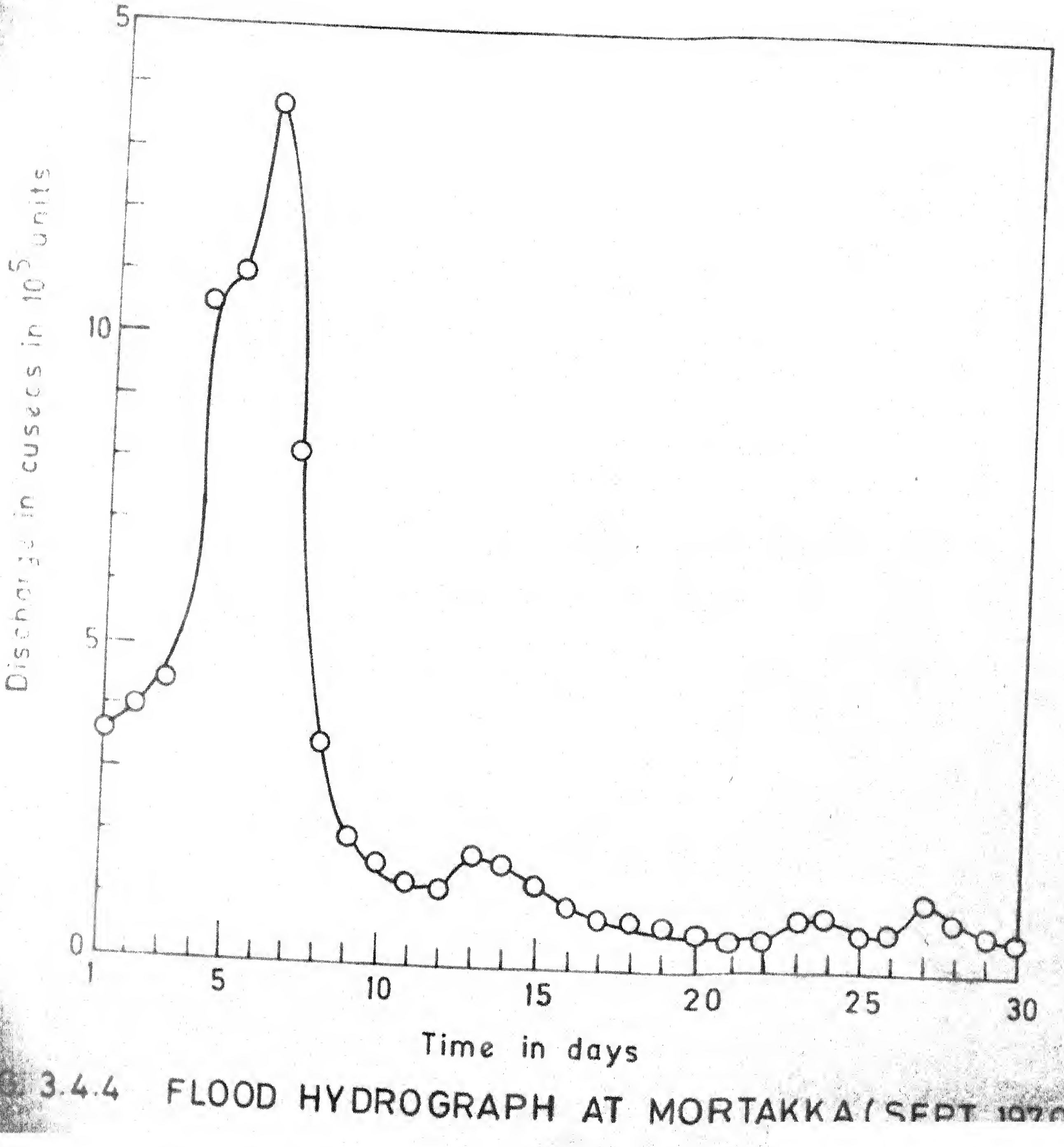


FIG. 3.4.3 FLOOD HYDROGRAPH AT MORTAKKA (SEPT. 1961)



3.4.4 FLOOD HYDROGRAPH AT MORTAKKA (SEPT 1970)

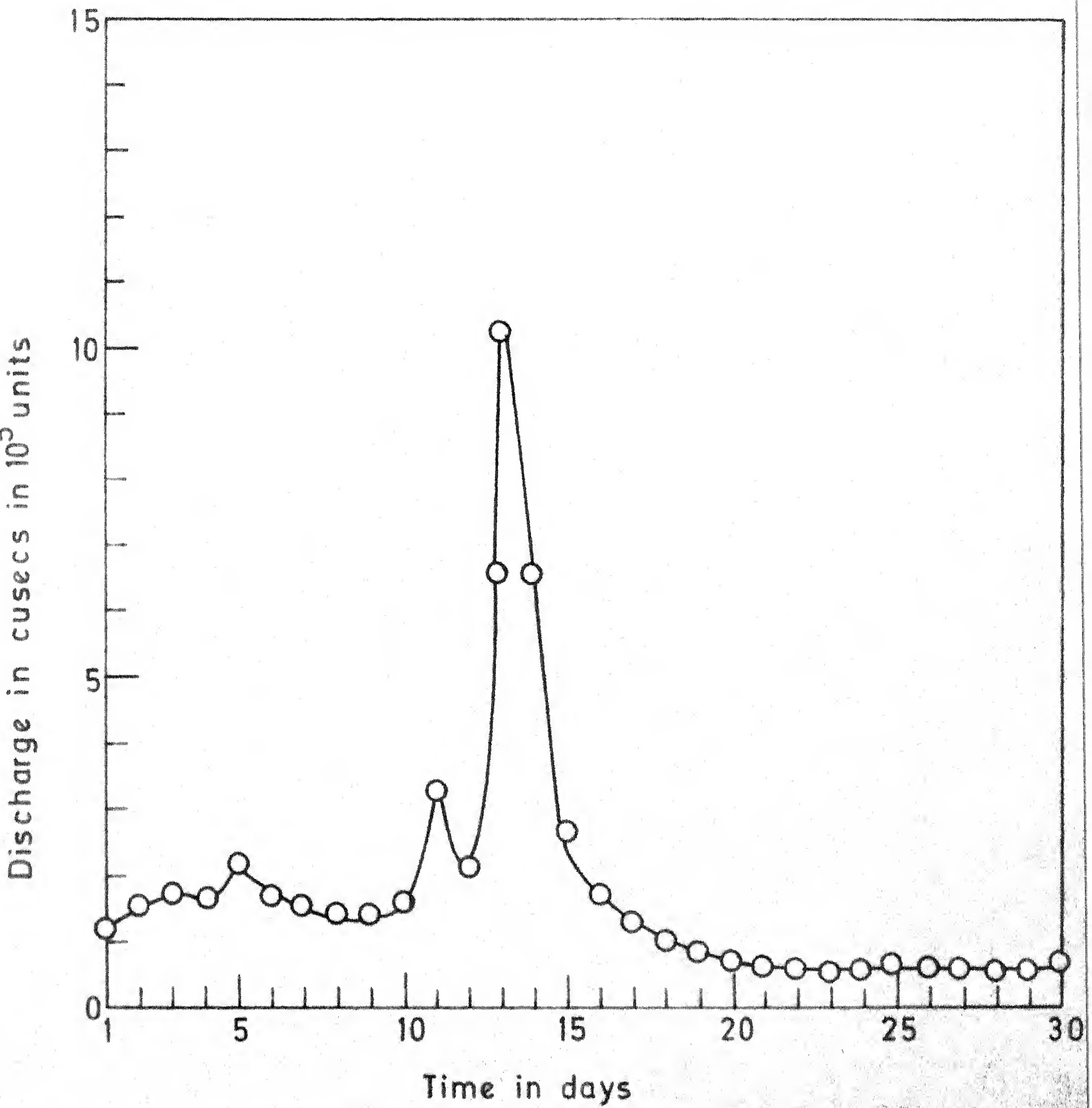


FIG. 3.4.5 FLOOD HYDROGRAPH AT MORTAKKA (SEPT 19

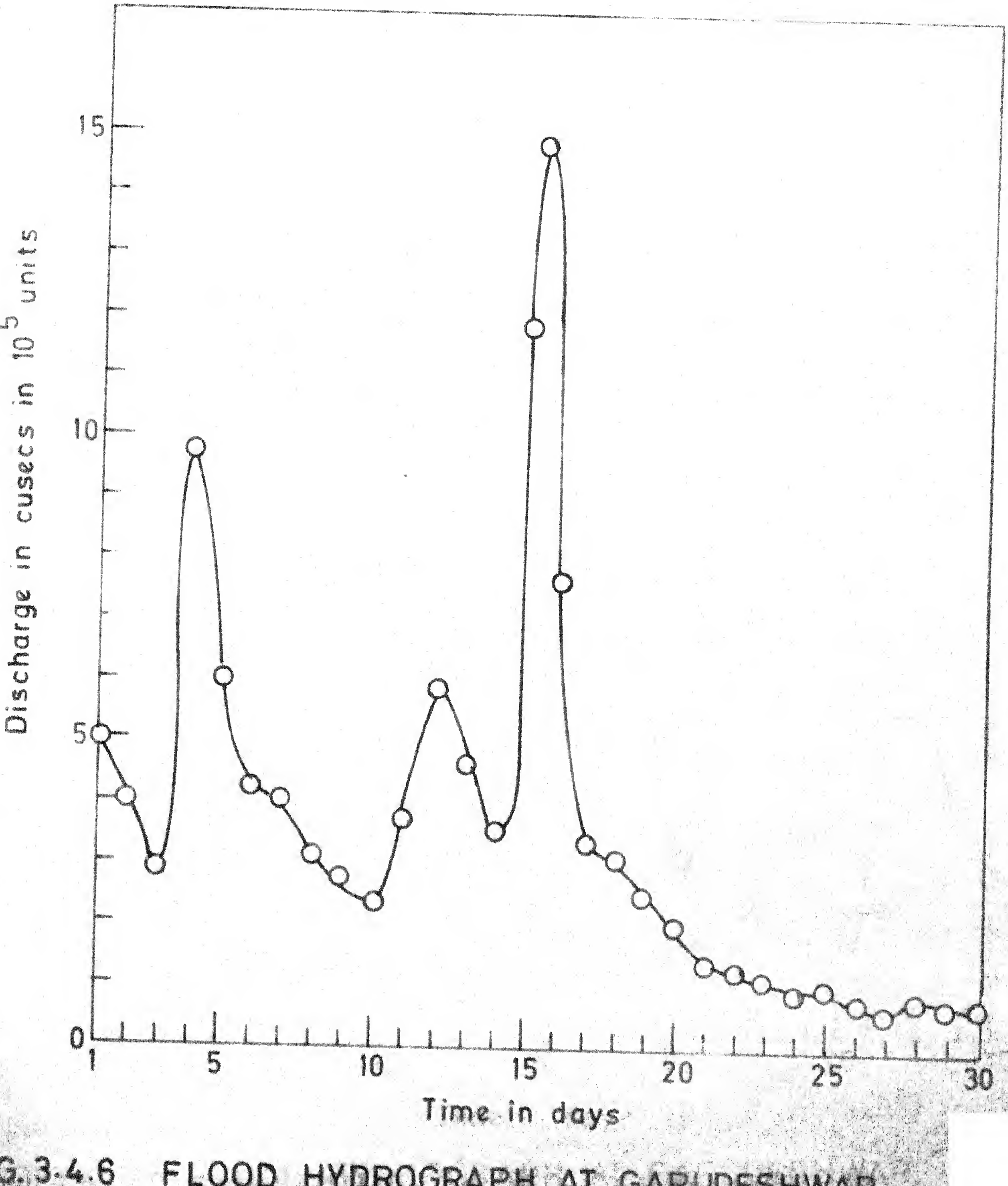


FIG. 3.4.6 FLOOD HYDROGRAPH AT GARUDESHWAR (SEPT. 1959)

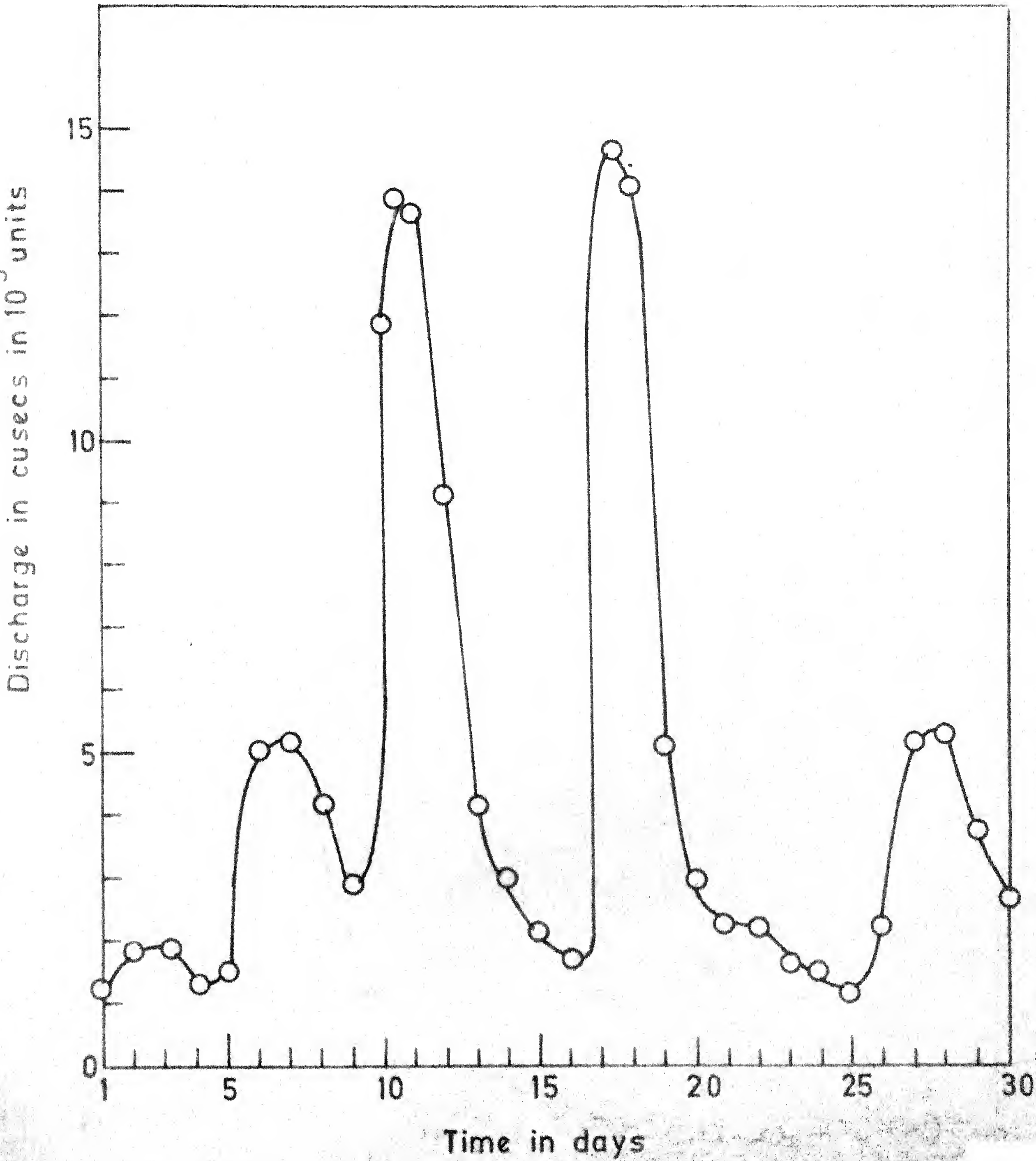


FIG. 3.4.7 FLOOD HYDROGRAPH AT GARUDESHWAR (SEPT. 1961)

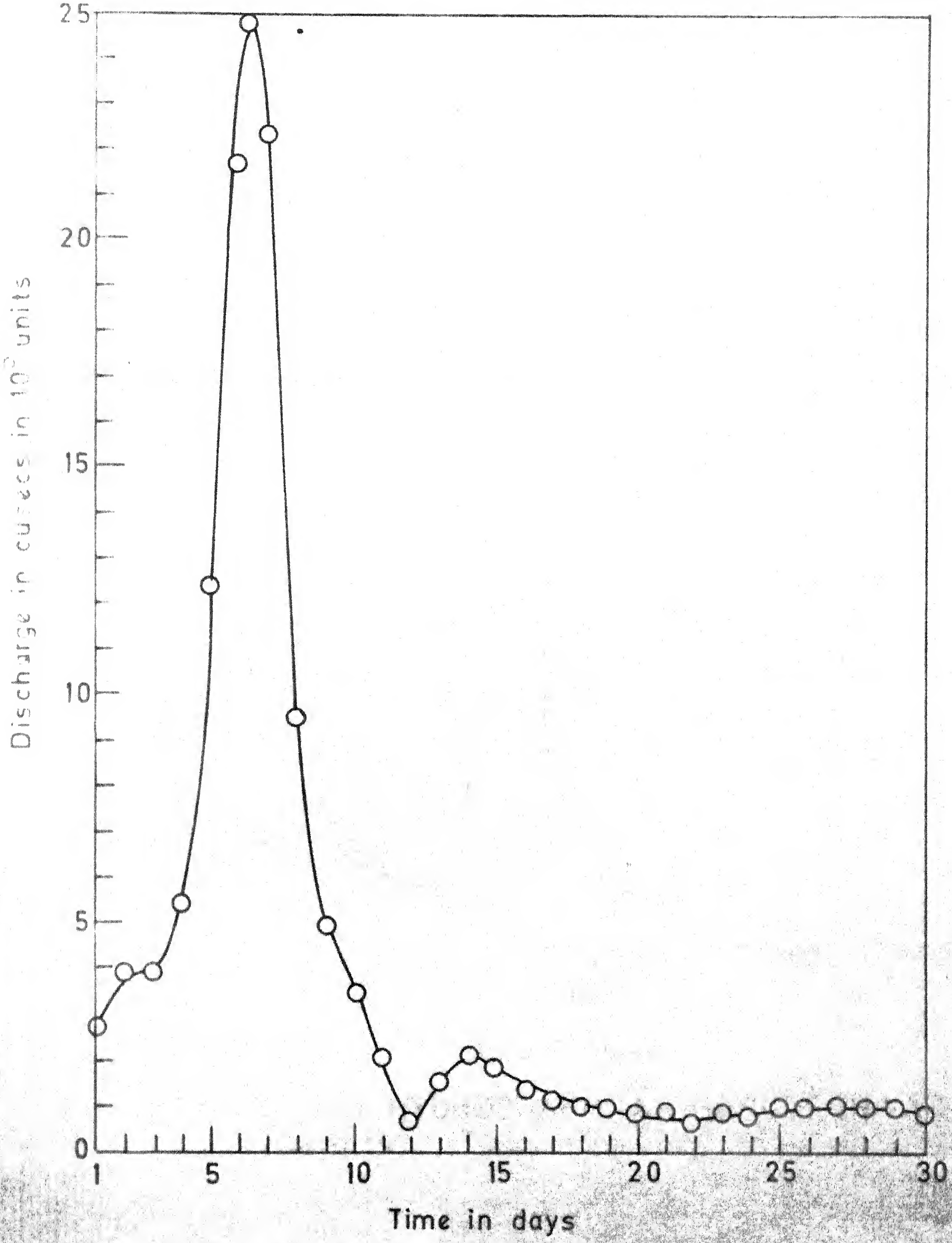


FIG. 3.4.8 FLOOD HYDROGRAPH AT GARUDESHWAR (SEPT. 1970)

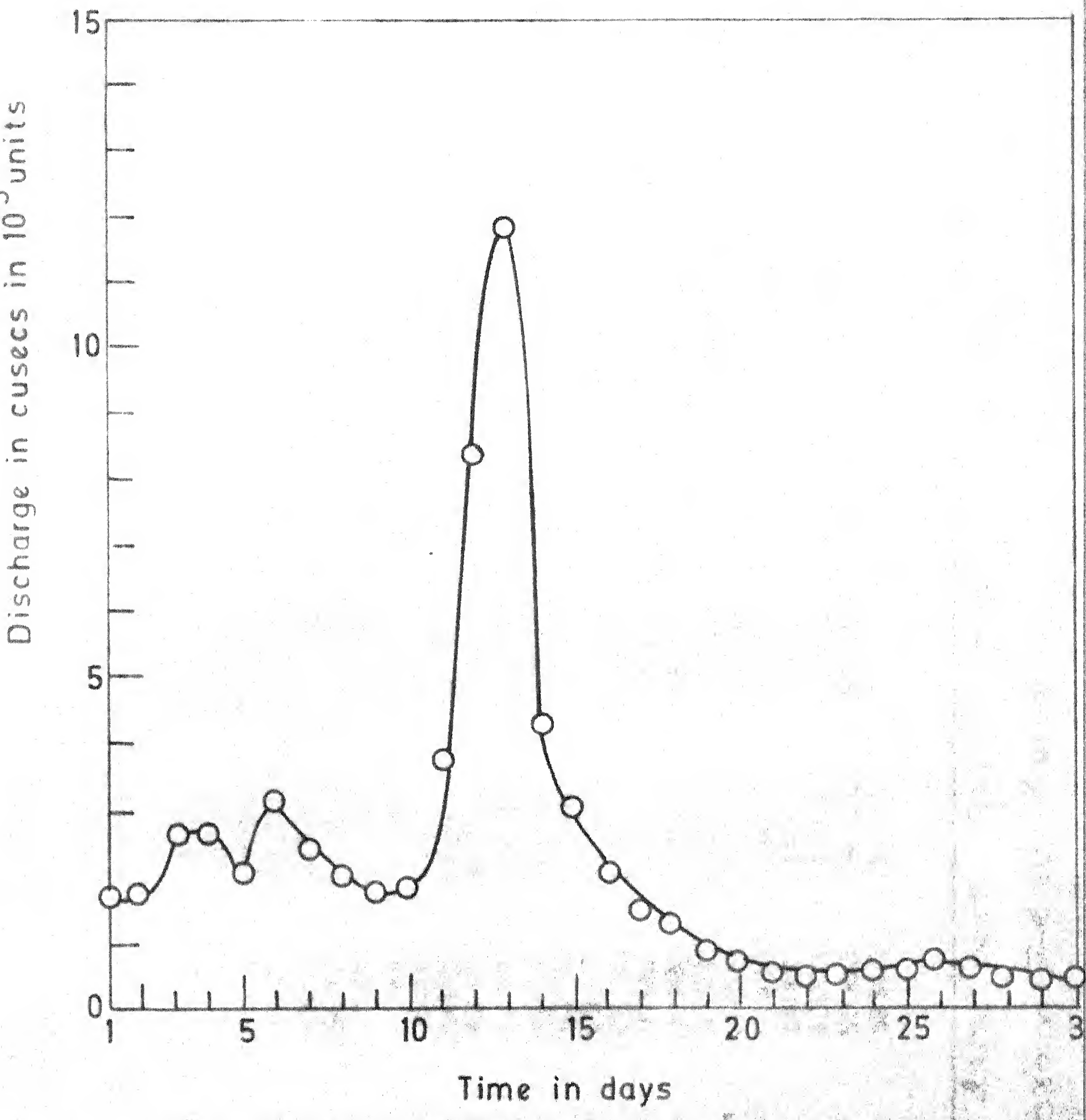


FIG. 3.4.9 FLOOD HYDROGRAPH AT GARUDESHWAR (Sept. 1975)

TABLE 3.4.18. 3-HOURLY STREAMFLOW DATA AT MORTAKKA, 1959 (SEPTEMBER)
(Flows in cfs)

275000	260000	245000	225000	213000	201000	188000	175000	215000	260000
300000	350000	300000	260000	215000	175000	195000	215000	235000	260000
400000	540000	680000	810000	750000	690000	630000	575000	515000	455000
395000	335000	228000	221000	213000	305000	299000	293000	287000	280000
276000	272000	268000	265000	261000	257000	253000	250000	251000	252000
253500	255000	256000	257000	258500	260000	251000	243000	234000	225000
207000	190000	173000	155000	155000	155000	155000	155000	156000	157000
158500	160000	176000	192000	208000	225000	243000	261000	279000	290000
305000	320000	335000	350000	365000	380000	395000	415000	411000	407000
403000	400000	394000	388000	382000	380000	365000	350000	335000	325000
333000	341000	350000	260000	264000	268000	272000	275000	281000	287000
293000	300000	318000	336000	354000	375000	545000	715000	895000	1040000
980000	920000	860000	800000	660000	520000	380000	255000	244000	233000
222000	210000	203000	296000	288000	180000	175000	170000	165000	160000
156000	152000	148000	145000	140000	135000	130000	125000	121000	117000
113000	110000	107500	105000	102500	100000	99000	98000	97000	95000
92500	90000	87500	85000	84000	83000	81500	80000	77800	75000
72500	75000	75000	75000	75000	75000	75000	75000	75000	75000
72500	70000	67500	65000	65000	65000	65000	65000	64000	63000
61500	60000	60000	60000	60000	60000	61000	62000	63500	65000
64000	63000	61500	60000	59000	58000	56500	55000	54000	53000
51500	50000	49000	48000	47000	45000	45000	45000	45000	45000
45000	45000	45000	45000	45000	45000	45000	45000	46000	47000
48500	50000	50000	50000	50000	50000	51000	52000	53500	55000
54000	52000	51500	51000						

streamflow data are given for a month at 3-hrs intervals starting from zero hour.

TABLE 3.4.19. 3-HOURLY STREAMFLOW DATA AT MORTAKKA, 1961 (SEPTEMBER)
(Flows in cfs)

100000	105000	110000	120000	130000	140000	150000	160000	157500	155000
152500	150000	147500	145000	142500	140000	136000	132000	128000	125000
125000	125000	125000	125000	133000	141000	150000	160000	180000	200000
220000	250000	270000	290000	310000	340000	350000	360000	370000	380000
377500	375000	372500	370000	367500	365000	362500	360000	351000	342000
333000	325000	313000	300000	287000	275000	260000	245000	230000	215000
208000	201000	193000	185000	200000	215000	230000	250000	330000	410000
490000	575000	725000	875000	1025000	1120000	1137000	1154000	1172000	1190000
1178000	1166000	1154000	1140000	1080000	1020000	960000	900000	840000	780000
720000	675000	605000	535000	465000	400000	370000	340000	310000	280000
260000	240000	225000	210000	200000	190000	180000	160000	166000	172000
178000	185000	170000	155000	140000	120000	119000	118000	117000	115000
123000	131000	140000	150000	156000	162000	168000	175000	425000	675000
925000	1150000	1160000	1170000	1180000	1190000	1170000	1150000	1130000	1100000
1000000	900000	800000	700000	620000	540000	460000	360000	345000	330000
315000	300000	288000	276000	264000	250000	230000	210000	190000	170000
170000	170000	170000	170000	170000	170000	170000	170000	165000	160000
155000	150000	146000	142000	138000	135000	132500	130000	127500	125000
125000	125000	125000	125000	122500	120000	117500	115000	114000	113000
112000	110000	112500	115000	117500	120000	124000	128000	132000	135000
139000	143000	147000	150000	157000	164000	171000	180000	198000	216000
234000	250000	265000	280000	295000	305000	310000	315000	320000	325000
324000	323000	322000	320000	302000	294000	276000	250000	225000	200000
175000	150000	152500	155000	157500	160000	162500	165000	167500	170000
169000	168000	167000	165000						

streamflow data are given for a month at 3-hrs intervals starting from zero hours.

TABLE 3.4.20. 3-HOURLY STREAMFLOW DATA AT MORTAKKA, 1970 (SEPTEMBER)
(Flows in cfs)

350000	365000	380000	400000	392000	383000	375000	365000	370000	375000
380000	385000	389000	393000	397000	400000	402500	405000	407500	410000
415000	420000	425000	430000	460000	490000	520000	550000	675000	800000
925000	1050000	1056000	1062000	1068000	1075000	1081000	1087000	1093000	1100000
1150000	1200000	1250000	1300000	1310000	1320000	1330000	1350000	1332000	1314000
1295000	1275000	1160000	1045000	930000	800000	730000	660000	580000	500000
460000	420000	380000	350000	330000	305000	290000	260000	255000	240000
225000	210000	202000	193000	186000	180000	175000	170000	165000	160000
154000	148000	141000	135000	132500	130000	127500	125000	124000	123000
122000	120000	120000	120000	120000	120000	127000	134000	142000	150000
157000	164000	172000	180000	187500	175000	172500	170000	167500	165000
162500	160000	156000	152000	148000	145000	141000	137000	133000	130000
126000	122000	118000	115000	111000	107000	103000	100000	99000	98000
97000	95000	94000	93000	92000	90000	89000	88000	87000	85000
82500	80000	77500	75000	75000	75000	75000	75000	74000	73000
72000	70000	69000	68000	67000	65000	65000	65000	65000	65000
64000	63000	62000	60000	60000	60000	60000	60000	59000	58000
57000	55000	54000	53000	52000	50000	55000	60000	65000	70000
72500	75000	77500	80000	80000	80000	80000	80000	81000	82000
83000	85000	86000	87000	88000	90000	89000	88000	87000	85000
84000	83000	82000	80000	81000	82000	83000	85000	90000	95000
100000	105000	109000	113000	117000	120000	117000	113000	109000	105000
99000	93000	87000	80000	77500	75000	72500	70000	66700	65000
62500	60000	60000	60000	60000	60000	59000	58000	57000	55000
56000	55500	55000	54000						

Streamflow data are given for a month at 3hrs interval starting from zero hour.

TABLE 3.4.21. 3-HOURLY STREAMFLOW DATA AT MORTAKKA, 1975 (SEPTEMBER)
(Flows in cfs)

100000	100300	100600	100900	111200	115000	120000	124397	125000	130000
135000	140000	144000	148000	152000	155780	157500	160000	162500	165000
167000	168500	170000	171380	171000	170600	170300	170000	167500	165000
162500	161990	165000	170000	175000	180000	186000	192000	198000	221000
215000	210000	205000	200000	190000	180000	170000	177380	177300	177200
177100	170000	165000	160000	155000	157580	155300	154000	152500	150000
147000	144000	140000	136400	136500	136500	136500	136500	136500	136600
136700	136820	137000	138000	139000	140000	144000	148000	152000	156000
176000	196000	216000	230000	250000	270000	295000	328540	320000	305000
285000	275000	280000	245000	230000	211870	411870	611870	811870	1029350
1005000	990000	975000	950000	910000	870000	830000	800000	750000	700000
650000	611750	550000	490000	430000	375000	350000	325000	300000	272300
258000	244000	230000	210000	205000	190000	175000	168700	160000	155000
150000	145000	140000	135000	132500	131560	128000	125000	122000	120000
115000	110000	105000	102550	100000	99500	97000	95000	93000	91000
89000	88285	86000	84000	82000	80000	79000	78000	77000	76035
74500	73000	71500	70000	69000	68000	67000	67600	67000	66500
66000	65000	64000	63000	62000	61000	60800	60600	60400	60000
59850	59700	59550	59340	59550	59700	59850	60000	60300	60600
60900	61320	60900	60600	60300	60000	64000	68000	72000	76600
73000	70000	67000	65000	64000	63000	62000	61920	59500	58000
56500	55000	54600	54200	53800	53940	53000	52000	51000	50000
51500	52300	53800	56090	56000	55700	55400	55000	55600	66200
66800	57430	58000	58600	59200	60000	61000	62000	63000	64600
64000	63500	63000	62000						

streamflow data are given for a month at 3hrs inte
starting from zero hour.

TABLE 3.4.22. 3-HOURLY STREAMFLOW DATA AT GARUDESHWAR, 1959 (SEPTEMBER) (Flows in cfs)

532011	510000	490000	468131	470000	480000	488000	494377	485000	470000
460000	459839	445000	430000	415000	407793	390000	375000	360000	353410
325000	310000	305000	283674	290000	300000	310000	329164	480000	640000
720000	978000	1030000	1080000	1130000	1190000	1040000	890000	740000	601528
575000	555000	525000	507439	480000	460000	440000	418529	420000	424000
428000	425678	420000	415000	410000	408532	375000	350000	325000	304745
305000	306000	307000	307856	290000	280000	270000	258200	260000	265000
270000	278964	260000	250000	240000	232821	232000	231700	230000	229000
220000	215000	210000	201521	240000	280000	320000	380527	400000	420000
440000	464469	500000	530000	560000	590560	570000	550000	530000	505127
490000	480000	470000	463728	445000	430000	415000	393761	380000	370000
360000	355350	354300	353000	352000	350360	550000	750000	950000	1175890
1270000	1370110	1300000	1240669	1120000	1000000	880000	759816	690000	630000
570000	500000	460000	420000	380000	327511	340000	360000	380000	408018
375000	350000	325000	307714	302000	298000	293000	290410	280000	270000
255000	247920	240000	230000	220000	208788	204000	200000	196000	199169
195000	190000	185000	186930	180000	170000	160000	144484	142000	140000
138000	131550	131600	131630	131670	131700	132400	133100	133800	144400
138000	132000	126000	120776	114000	108000	101000	93950	93600	93500
93400	93270	93000	92500	92000	91975	93000	95000	97000	98765
98800	98840	98880	68925	72500	73000	75500	80121	76000	72000
68000	64923	63000	62000	61000	60700	60900	61100	61300	61680
66000	71000	76000	80800	78000	76000	74000	73055	72000	71000
70000	69650	70000	70400	70800	71696	72000	73000	74000	75900
75000	74500	74000	73000						

Streamflow data are given for a month at 3hrs interv
starting from zero hour.

TABLE 3.4.23. 3-HOURLY STREAMFLOW DATA AT GARUDESHWAR, 1961 (SEPTEMBER)
(Flows in cfs)

100000	105000	110000	115130	117000	119000	121000	122300	130000	135000
140000	145689	150000	160000	170000	181075	180600	110100	199700	179382
181000	182000	183000	183560	175000	173000	165000	152670	146000	140000
134000	128870	134000	138000	143000	149280	150000	152000	153000	154410
220000	290000	360000	437140	455000	470000	485000	505375	490000	480000
470000	458835	470000	482000	495000	510100	505000	500000	495000	491875
470000	450000	430000	410570	395000	38000	365000	346400	330000	315000
300000	283130	280000	275000	270000	267900	220000	180000	140000	1189170
1290000	1382364	1417000	1458810	1440000	1422000	1404000	1376780	1320000	1270000
1230000	1198100	1130000	1060000	990000	916680	870000	830000	790000	738190
660000	590000	520000	425310	415000	405000	395000	388940	375000	350000
325000	299030	275000	260000	255000	233880	230000	220000	210000	214400
202000	190000	178000	165390	166000	167000	168000	169560	360000	560000
780000	984875	1100000	1220000	1340000	1445455	1467000	1488000	1509000	1530390
1500000	1470000	1440000	1410000	1350000	1290000	1230000	1162950	1000000	840000
680000	520640	490000	460000	425000	393330	368000	343000	318000	292890
284000	276000	268000	260540	255000	250000	245000	238290	240200	242200
244200	246440	239000	232000	226000	218180	215000	211000	208000	203130
195500	188500	181500	173600	173500	173400	173350	173610	169000	165000
161000	158225	154000	150000	146000	140190	136000	132000	128000	124700
150000	170000	190000	210750	215000	220000	230000	231370	250000	270000
290000	319190	360000	410000	460000	521725	510000	495000	470000	459300
480000	500000	520000	545235	540000	535000	530000	524570	490000	455000
420000	380210	365000	350000	335000	310185	310000	300000	290000	282400
280000	275000	270000	270000						

Streamflow data are given for a month at 3-hrs intervals starting from zero hour.

TABLE 3.4.24. 3-HOURLY STREAMFLOW DATA AT GARUDESHWAR, 1970 (SEPTEMBER)
(Flows in cfs)

400000	405000	410000	412560	380000	350000	320000	278940	280000	281500
283000	284412	300000	320000	340000	370650	373000	376000	379000	381240
379000	377000	375000	373474	375000	377000	379000	381240	420000	460000
500000	540090	560000	580000	600000	621280	770000	920000	1070000	1242913
1400000	1500000	1600000	1715580	1900000	2000000	21000000	2153300	220000	2300000
2400000	2449820	2390000	2340000	2290000	2252140	2080000	1950000	1780000	1581440
1430000	1280000	1130000	960160	900000	840000	780000	727180	670000	620000
570000	508320	470000	440000	410000	384770	380000	375000	370000	367120
350000	340000	330000	310640	290000	270000	250000	223802	220000	215000
210000	217095	182000	135000	100000	68480	98000	128000	150000	172264
166000	162000	158000	153556	155000	158000	150000	147200	165000	185000
205000	218860	220300	220500	220700	220980	213000	206000	199000	190830
190000	188500	188000	188714	180000	170000	160000	148260	146000	144000
142000	141200	140000	135000	130000	127080	124000	122000	120000	112960
112800	112900	113000	113170	112000	111000	111000	110560	108000	106000
105000	104630	104000	103500	103000	102964	100000	98000	96000	93440
93000	92000	91000	89060	86000	83000	80000	78400	75000	72000
69000	66960	66900	66800	66850	66964	65800	64700	63600	62480
69000	76000	83000	91074	88000	85000	82000	79425	79000	78500
78500	78370	82000	86000	90000	95310	97000	99000	101000	104135
104000	103800	103600	103430	103000	102800	102500	102370	103000	104000
105000	106606	105000	104000	103000	103430	100500	97500	95000	92486
98000	104000	110000	114370	115000	116000	117000	117196	113000	109000
105000	101664	97000	93000	89000	87544	85000	82500	80000	75190
75500	76000	76500	77000						

streamflow data are given for a month at 3hrs inter
starting from zero hour.

TABLE 3.4.25. 3-HOURLY STREAMFLOW DATA AT GARUDESHWAR, 1975 (SEPTEMBER)
(Flows in cfs)

190000	200000	210000	227086	205000	190000	175000	169860	169600	169200
169000	168910	169000	169200	169400	169650	166000	163000	160000	156344
180000	210000	240000	262350	263000	264000	265000	265420	265200	265000
264800	264500	250000	240000	230000	223590	220000	215000	210000	208550
210000	220000	230000	244240	260000	280000	300000	312760	310000	300000
290000	296450	282000	265000	250000	236830	230000	220000	210000	203190
202000	201000	200000	208450	204000	200000	196000	190760	185000	180000
175000	169760	170000	170500	171000	172020	174000	176000	178000	180280
182000	184000	186000	188925	230000	275000	320000	369980	350000	330000
310000	304570	430000	570000	710000	840270	900000	960000	1020000	1074460
1100000	1130000	1160000	1189610	1090000	1010000	930000	844620	740000	640000
540000	430410	415000	400000	385000	376930	350000	330000	310000	297050
280000	270000	260000	254325	240000	230000	220000	214800	200000	190000
180000	179250	174000	168000	162000	156060	153000	150000	147000	144980
141000	138000	135000	132230	130000	125000	120000	117510	111000	105000
99000	91590	88000	85000	82000	78860	78500	78200	78000	77770
77000	76000	75000	73425	71000	69000	67000	64280	61000	58000
55000	50480	52000	53500	55000	56590	55500	54500	53500	52990
52000	51500	51000	50480	54000	57000	60000	64390	61000	58000
55000	52990	54000	54800	55600	56800	58000	59000	60000	60500
61000	62000	63000	63500	66000	69000	72000	75275	73000	71000
69000	66330	65000	64000	63000	61490	59500	58000	56500	55450
55000	54000	53000	52280	50000	49000	48000	47865	47300	46800
46300	46770	47000	48000	49000	49280	49000	49500	49000	48110
48500	49000	49500	50000						

Streamflow data are given for a month at 3hrs int
starting from zero hour.

TABLE 3.4.26. 79 YEARS ANNUAL SERIES AT SARDAR SAROVAR DAM SI
ARRANGED IN ASCENDING ORDER

Sl. No.	Water year	Inflow MAF	Sl. No.	Water year	Inflow MAF	Sl. No.	Water year	Infl MAF
1	1899-1900	4.85	28	1901-02	29.74	55	1955-56	40.
2	1965-66	9.92	29	1921-22	29.97	56	1936-37	40.
3	1966-67	15.53	30	1967-68	30.00	57	1938-39	41.
4	1951-52	16.23	31	1914-15	30.85	58	1947-48	41.
5	1941-42	17.88	32	1954-55	30.96	59	1943-44	41.
6	1904-05	18.03	33	1922-23	31.10	60	1948-49	42.
7	1907-08	18.61	34	1935-36	31.59	61	1937-38	42.
8	1918-19	19.58	35	1908-09	31.60	62	1969-70	42.
9	1957-58	19.68	36	1927-28	31.68	63	1892-93	43.
10	1902-03	19.77	37	1929-30	31.99	64	1934-35	43.
11	1920-21	21.00	38	1950-51	32.43	65	1923-24	43.
12	1952-53	21.44	39	1903-04	32.48	66	1946-47	44.
13	1909-10	22.24	40	1928-29	32.69	67	1894-95	44.
14	1911-12	22.56	41	1906-07	32.85	68	1942-43	45.
15	1895-96	22.58	42	1949-50	33.19	69	1931-32	45.
16	1953-54	22.92	43	1896-97	33.58	70	1893-94	46.
17	1963-64	23.14	44	1900-01	34.03	71	1926-27	46.
18	1962-63	24.78	45	1898-99	34.64	72	1933-34	46.
19	1968-69	26.71	46	1924-25	34.90	73	1916-17	46.
20*	1958-59	27.01*	47	1939-40	35.06	74	1917-18	48.
21	1905-06	27.03	48	1956-57	35.17	75	1919-20	52.
22	1912-13	27.05	49	1932-33	35.35	76	1959-60	53.
23	1964-65	27.90	50	1910-11	35.38	77	1891-92	54.
24	1897-98	28.80	51	1930-31	37.11	78	1944-45	59.
25	1960-61	28.82	52	1940-41	37.20	79	1961-62	60.
26	1925-26	29.35	53	1945-46	38.23			
27	1913-14	29.69	54	1915-16	39.37			

* 75 percent dependable flow.

CHAPTER 4

OPTIMIZATION MODEL

4.1. Introduction

Various optimization models have been described in Chapter 2. As mentioned therein optimization models can be used to screen alternatives. Decision makers can examine a wide range of alternatives and select the most desirable one. The discontinuous linear programming technique is selected for application to the present problem for screening the alternatives.

4.2. Formulation of the Model

4.2.1. Physical system

For proper utilisation of water resources of the Narmada river basin a master plan was prepared by Madhya Pradesh in 1972, in which 32 reservoir sites were proposed as shown in the report of the Narmada Water Dispute Tribunal (NWDT), Volume V. Out of these, 31 reservoir sites were in Madhya Pradesh and one was in Gujarat. The tribunal has awarded 18.25 MAF of water to Madhya Pradesh, 9.0 MAF of water to Gujarat, 0.5 MAF of water to Rajasthan and 0.25 MAF of water to Maharashtra. Gujarat has planned to utilize its share of water by building a reservoir, namely Sardar Sarovar at Navagam. This reservoir will also provide Rajasthan's share of water. Madhya Pradesh has planned to build several reservoirs across the main stream, and across the tributaries. A few of these are listed below:

Reservoirs on tributaries		Reservoirs on main river	
(a)	Barna	(a)	Upper Narmada
(b)	Tawa	(b)	Ragavapur
(c)	Chhota tawa	(c)	Rosra
(d)	Dudhi	(d)	Basania
(e)	Kolar	(e)	Bargi
(f)	Man	(f)	Chinki
(g)	Jobat	(g)	Narmadasagar
		(h)	Omkareshwar
		(i)	Maheshwar
		(j)	Sardar Sarovar

There are 10 major reservoirs planned along the main stem of river Narmada. Out of these, 4 are purely hydro-power projects and remaining six are multipurpose projects.

As already stated earlier, the Narmada river basin is divided into three zones. The upper zone extends up to Bargi, middle zone from Bargi to Narmadasagar, and lower zone below Narmadasagar. All the utilisation upstream of the Bargi reservoir are assumed to be clubbed into the Bargi. The water requirements at and above Narmadasagar are to be met by the Narmadasagar reservoir. The water requirements to be met by Omkareshwar and water requirements up to Sardar Sarovar are clubbed at Omkareshwar. Maheshwar is planned as hydropower project.

It is very difficult to accommodate all the planned reservoirs in the formulation of linear programming model, because of the large size involved. It requires not only a

large amount of computer time but also adds complexity in the formulation. Therefore it is desirable to incorporate a small number of major reservoirs into the model, and to club several smaller reservoir into a larger one.

From the hydrological and agricultural considerations, the water year is considered from 1st of July to 30th of June of next calender year. Keeping in view the above mentioned facts five reservoirs and four seasons in a year are used in the formulation of LPD model for the Narmada river basin under study.

4.2.2. System representation

The schematic diagram for the LPD model is shown in Figure 4.2. The description of the model is as follows:

(a) Numbers 1, 2, 3, 4, and 5 represent the reservoir sites;

(b) $f_{i,t}$ indicates inflow due to the independent catchment area of reservoir site i, during time t;

(c) I_i is the annual irrigation target at reservoir site i;

(d) $K_{i,t}\ I_i$ is the proportion of irrigation demand I at reservoir site i, during time t;

(e) $K'_{i,t}\ I_i$ is the return flow from irrigation utilisation at reservoir site i, during time t;

(f) $a_{i,t}$ is the release to meet irrigation requirements at reservoir site i, during time t;

(g) $c_{i,t}$ indicates release to meet energy requirements at reservoir site i, during time t;

(h) E_i shows the firm energy target at reservoir site i.

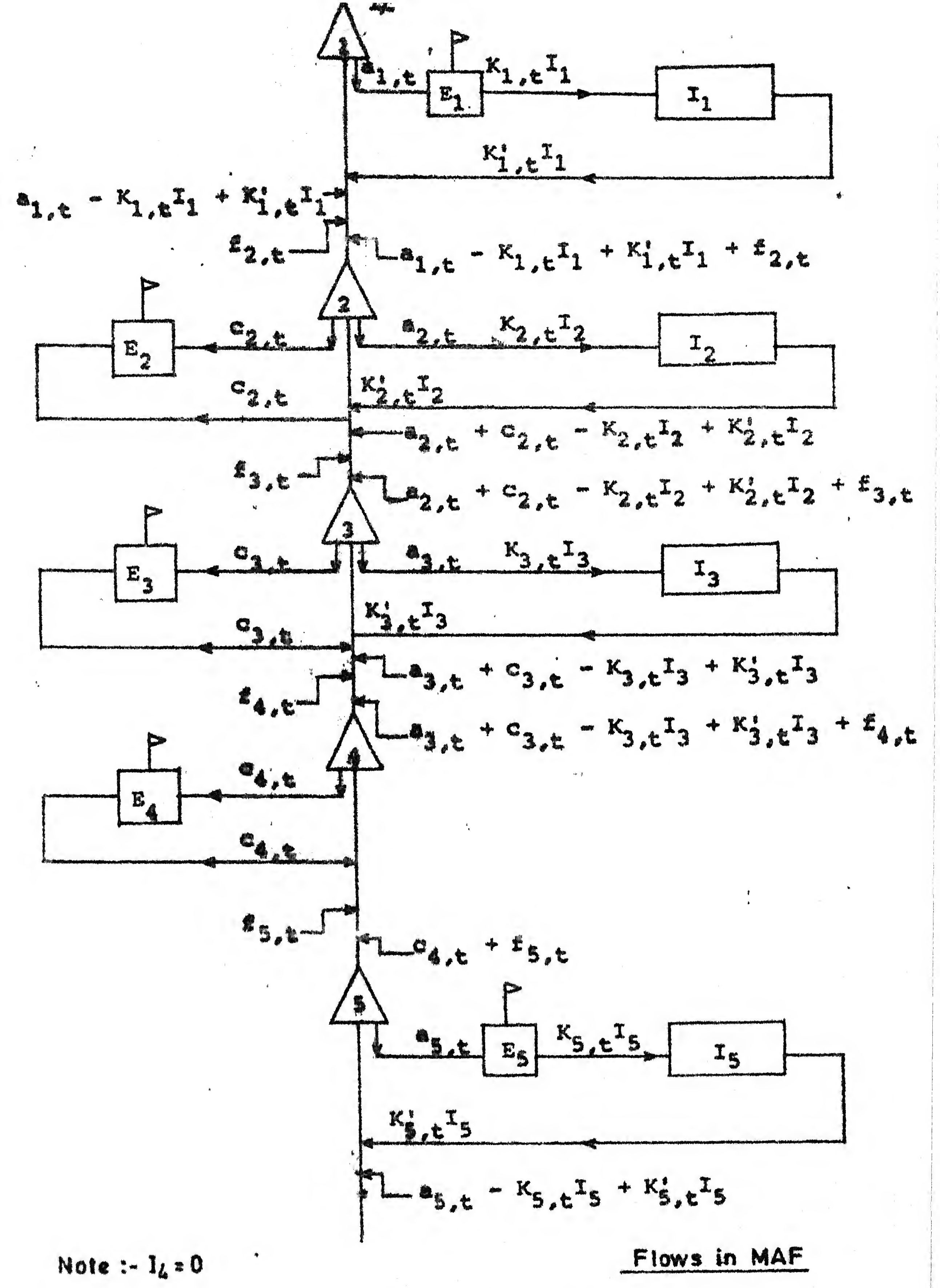


FIG. 4.2 SCHEMATIC DIAGRAM FOR LPD MODEL FOR FINAL STAGE OF DEVELOPMENT

4.3. Demands

4.3.1. Irrigation

The term 'water requirement' and 'water demand' will be used interchangeably to mean those quantities that a given water resource project is expected to deliver under specified condition of allowable shortages. The types of major water demands most commonly found in developing countries are demand for irrigation and power generation. A deterministic approach has been used for their estimation.

In order to estimate irrigation water requirements, it is necessary to know the proposed cropping pattern in the command area. After taking into consideration the existing and the proposed cropping pattern, the NWDT award has decided for major, medium, minor, microminor and pumping schemes the following deltas: 2.56 ft for major, 2.07 ft for medium, 1.89 ft for minor, 1.50 ft for microminor and 2.56 ft for pumping schemes at the head regulator. The areas to be covered under each are taken from the data available from the report of the NWDT Volume I. The water requirements for irrigation, and industrial and domestic water supply at each reservoir site are given in Tables 4.3.1 to 4.3.4.

4.3.2. Hydropower

The energy requirements are calculated on the basis of proposed installed capacities of turbines and load factor. The load factor is assumed as 0.60. The actual energy produced is given by below:

TABLE 4.3.1. MONTHLY DISTRIBUTION OF WATER REQUIREMENTS AT AND ABOVE BARGI DAM

Sl. No.	Month	Medium, minor and pumping schemes		Major projects excluding Bargi		Demands to be met by Bargi dam only		Total (4)+(6)+(8)	Percentage demand in each month	Percentage demand in each season
		%	cfs	%	cfs	%	cfs	cfs	%	%
1	2	3	4	5	6	7	8	9	10	11
1	July	20	3425	4.06	415	3.91	1490	5330	8.15	
2	Aug	20	3425	4.06	415	3.42	1301	5141	7.85	27.91
3	Sept	30	5138	5.28	539	5.56	2117	7794	11.91	
4	Oct	15	2569	7.58	774	6.85	2607	5950	9.09	
5	Nov	3.5	600	16.35	1669	17.17	6542	8811	13.48	33.82
6	Dec	3.5	600	15.16	1548	13.69	5214	7362	11.25	
7	Jan	2.0	343	13.31	1359	11.65	4437	6139	9.38	
8	Feb	2.0	343	7.61	777	11.90	4536	5656	8.65	22.72
9	March	1.0	171	6.49	663	5.87	2235	3069	4.69	
10	April	1.0	171	6.73	687	7.07	2694	3552	5.43	
11	May	1.0	171	7.58	774	6.85	2607	3552	5.43	15.55
12	June	1.0	171	5.78	590	6.06	2309	3070	4.69	
	Total	100.0	17127	100.0	10211	100.0	38089	65427 (3.960 MAF)	100.00	100.00

Source : NWDT REPORT VOL I

TABLE 4.3.2. MONTHLY DISTRIBUTION OF WATER REQUIREMENTS AT AND ABOVE NARMADASAGAR (N.S.)

Sl. No.	Month	Medium, minor and pumping schemes		Industrial and domestic supply excluding N.S.		Major dams excluding N.S.		Irrigation + industrial and domestic demand to be met by N.S.		Total (4)+(6)+(8)+(10)	Percentage demand in each month	Percentage demand in each season
		%	cfs	%	cfs	%	cfs	%	cfs	cfs	%	%
1	2	3	4	5	6	7	8	9	10	11	12	13
1	July	17.05	11124	7.89	1220	8.85	6131	6.86	1496	19971	11.62	
2	Aug	14.76	9628	7.89	1220	7.53	5220	5.89	1285	17353	10.10	40.64
3	Sept	34.65	22603	8.15	1260	9.92	6873	8.09	1765	32501	18.92	
4	Oct	27.22	17759	8.74	1350	10.09	6993	8.79	1919	28021	16.31	
5	Nov	0.36	235	9.03	1395	13.94	9663	15.17	3311	14604	8.50	31.33
6	Dec	0.32	211	8.74	1350	10.21	7075	11.78	2570	11206	6.52	
7	Jan	0.73	472	8.74	1350	8.28	5741	9.84	2147	9710	5.65	
8	Feb	0.85	558	8.74	1350	7.06	4898	8.67	1891	8697	5.06	15.68
9	March	1.00	650	7.89	1220	7.46	5172	6.86	1496	8538	4.97	
10	April	1.03	672	8.15	1260	5.43	3764	6.08	1328	7024	4.09	
11	May	1.00	650	7.89	1220	5.10	3529	5.89	1285	6684	3.89	12.35
12	June	1.03	672	8.15	1260	6.13	4251	6.08	1328	7511	4.37	
	Total	100.00	65234	100.00	15455	100.00	69310	100.00	21821	171820 (10.390 MAF)	100.00	100.00

SOURCE: NWDT REPORT VOL I

TABLE 4.3.3. MONTHLY DISTRIBUTION OF WATER REQUIREMENTS AT AND BELOW OMKARESHWAR BUT UP TO SARDAR SAROVAR

Sl. No.	Month	Medium, minor and pumping schemes		Industrial and domestic supply		Major dams excluding Omkareshwar		Demand to be met by Omkareshwar		Maharashtra's share		Total (4)+(6)+(8)+(10)+(12)	Percentage demand in each month	Perce ntage deman in eac seaso
		%	cfs	%	cfs	%	cfs	%	cfs	%	cfs	cfs	%	%
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	July	19.81	5936	7.80	683	6.84	471	6.83	1285	-	-	8375	12.22	
2	Aug	14.81	4440	7.80	683	5.90	406	5.88	1106	-	-	6635	9.67	40.2
3	Sept	32.69	9798	8.06	706	8.06	555	8.13	1529	-	-	12588	18.35	
4	Oct	24.69	7400	8.92	781	8.75	602	8.82	1659	29.36	1220	11662	17.00	
5	Nov	1.01	302	9.22	807	15.15	1043	15.18	2857	8.08	336	5345	7.79	31.7
6	Dec	0.97	293	8.92	781	11.81	813	11.75	2212	15.66	651	4750	6.93	
7	Jan	0.97	293	8.92	781	9.92	683	9.85	1854	15.66	651	4262	6.21	
8	Feb	1.08	324	8.63	756	8.63	594	8.71	1639	19.50	810	4123	6.01	16.9
9	March	0.97	293	7.80	683	6.84	471	6.83	1285	11.74	488	3220	4.69	
10	April	1.01	302	8.06	706	6.10	420	6.07	1143	-	-	2571	3.75	
11	May	0.97	293	7.80	683	5.90	406	5.88	1106	-	-	2488	3.63	11.1
12	June	1.01	302	8.06	706	6.10	420	6.07	1143	-	-	2571	3.75	
	Total	100.00	29976	100.00	8756	100.00	6884	100.00	18818	100.00	4156	68590 (4.15 MAF)	100.00	100.0

SOURCE: NWDT REPORT Vol

TABLE 4.3.4. MONTHLY DISTRIBUTION OF WATER REQUIREMENT AT SARDAR SAROVAR

Sl. No.	Month	Demands to be met by Sardar Sarovar		Rajasthan's share		Total (4) + (6)	Percentage demand in each month	Percenta demand i each sea
		%	cfs	%	cfs	cfs	%	%
1	2	3	4	5	6	7	8	9
1	July	5.30	7920	-	-	7920	5.02	
2	Aug	6.26	9368	-	-	9368	5.93	19.34
3	Sept	8.85	13243	-	-	13243	8.39	
4	Oct	9.32	13938	29.35	2439	16377	10.37	
5	Nov	12.72	19024	8.08	672	19696	12.48	34.90
6	Dec	11.85	17727	15.66	1301	19028	12.05	
7	Jan	10.87	16263	15.66	1301	17564	11.13	
8	Feb	10.96	16385	19.50	1621	18006	11.40	29.31
9	March	6.50	9725	11.75	976	10701	6.78	
10	April	7.38	11041	-	-	11041	6.99	
11	May	5.61	8392	-	-	8392	5.32	16.45
12	June	4.37	6537	-	-	6537	4.14	
	Total	100.00	149563	100.00	8310	157873 (9.50 MAF)	100.00	100.00

SOURCE: NWDT REPORT VOL :

4.3.3. Industrial and domestic water

The quantity of water requirement for industrial and domestic water supply is taken from the NWDT, Volume I. Nearly uniform distribution throughout the year is assumed and is included in Tables 4.3.1 to 4.3.4.

4.4. Objective Function

Many theoretical and practical approaches have been proposed for identifying and quantifying objectives in water resources planning. It is a tedious and frustrating process to incorporate them into multiobjective planning models. It is a challenging job for the system analyst to recommend a single planning alternative for adoption (Loucks, et al., 1981). Marglin states, "In view of the three dimensional nature of national welfare -- the size of the economic pie, its division, and the method of slicing -- we believe it unwise to attempt to define a single index for the broad objective; instead we shall develop alternative objectives for the most important ways in which water development can contribute to national welfare. These are broadly two: efficiency, which expresses the objective of optimization of national income, and income redistribution, which expresses the objective of achieving a desired slicing of the economic pie by a knife that suit community values" (Maass, et al., 1962).

In the present study, the efficiency objective has been used. This objective requires an evaluation of costs incurred in building and operating the system, and benefits reaped from the system.

4.4.1. Construction of cost and benefit functions

Evaluation of benefits from a system is a tough task for the systems analyst. For the estimation of benefit from irrigation, the proposed cropping pattern, command area and price of irrigation water (Rs./acre foot) are the basic requirements. Similarly projected energy demands and unit price/kwhr are necessary for determination of gross benefits from energy. Due to lack of economic data of the projects, the following procedure has been adopted to develop cost and benefit functions. Bargi project is chosen to illustrate the procedure.

The Tribunal has assumed 45 years for the full development of the Narmada basin. It is suggested by the Tribunal that the award be reviewed after 45 years. The basin is planned to be developed in three stages. The first stage extends up to first 10 years. The second stage is from the 11th year to 30th year and the third stage from 31st year to 45 year.

A time horizon of 70 years is assumed in the analysis, including construction period. A discount rate of 5% is assumed. The operation, maintenance and replacement (OMR) costs for irrigation are assumed on a unit basis, i.e., Rupees per unit area to be irrigated at different reservoir sites. Similarly OMR costs for power are assumed on a unit basis, i.e., Rupees per unit installed capacity of turbines at various reservoir sites.

The rate of development of irrigation is represented by Figure 4.4.1. Since the costs and benefits are non-uniform

over the time horizon, it is necessary to use one of the three commonly used methods namely the present worth method, annual-cost method, or the internal rate of return method, for comparison of costs and benefits. In the present analysis, the annual-cost method is adopted. The details are given below:

(a) Annual benefit from irrigation: See Figure 4.4.1.

$$\begin{aligned} ABF = \Big[&0.2(P/A, 5, 10) \times (P/F, 5, 6) + 0.03(P/G, 5, 10) \\ &\times (P/F, 5, 6) + 0.5(P/A, 5, 20) \times (P/F, 5, 16) + \\ &0.02(P/G, 5, 20) \times (P/F, 5, 16) + 0.9)P/A, 5, 15) \\ &\times (P/F, 5, 36) + 0.0066(P/G, 5, 15) \times (P/F, 5, 36) \\ &+ 1(P/A, 5, 19) \times (P/F, 5, 51)\Big] \times (A/P, 5, 70); \end{aligned}$$

where ABF stands for annual benefit factor for irrigation, P/A for series present-worth factor, P/G for uniform-gradient-series present-worth factor, P/F for single-payment present-worth factor, and, A/P for capital-recovery factor. Using 5% discount rate and the rate of development as shown in Figure 4.4.1, ABF works out to be 0.46. A delta of 2.57 ft at the head regulator and an intensity of irrigation of 135% are assumed in calculating irrigation water requirements. The long term irrigation benefit is taken as Rs. 418/acre irrigated. Therefore the benefit per acre ft of water will be

$$\frac{418}{2.57 \times 1.35} = \text{Rs. } 120.48/\text{acre ft or}$$

Rs. 120.48 x 10^6/MAF. Annual benefit from irrigation will be Rs. 120.48 x 10^6 x ABF per MAF, i.e., Rs. 10 x 10^7 x 0.46 = Rs. 5.546 x 10^7/MAF.

(b) Annual cost of irrigation works:

Irrigation cost for continuing projects is taken from the Journal of Irrigation and Power, Volume 3, 1978, p. 95, as Rs. 3360/hectare for Madhya Pradesh where Bargi is situated. Assuming a uniform expenditure over 20 year development period and a time horizon of another 50 years, the annual capital cost recovery works out to be Rs. 1.2672 x 10^7/MAF.

(c) Operation, maintenance and replacement (OMR) cost:

OMR cost is assumed as Rs. 6/acre, i.e., Rs. 1.734/acre ft, or Rs. 0.1734 x 10^7/MAF.

(d) Reservoir cost:

For Bargi reservoir, the capital cost is 112.5 crores. The gross storage is 3.28 MAF.

$$\therefore \quad \text{Capital cost/MAF} = \frac{112.5}{3.28} = \text{Rs. } 34.30 \times 10^7/\text{MAF}$$

Assume a construction period of 6 years, discount rate 5%, and, total time horizon of 70 years. Using these,

the annual capital cost recovery works out to be 1.51×10^7/MAF.

(e) Annual cost of energy:

At present there is a provision for producing energy from Bargi dam by providing canal head power house (CHPH).

Proposed capacity of left side CHPH: $2 \times 7.5 = 15.0$ MW

Capital cost chargeable to power = 37.5 crores

$$\therefore \quad \text{Cost/kw installed} = \frac{37.5 \times 10^7}{15 \times 1000} = \text{Rs. } 2500/\text{kw}$$

$$\therefore \quad \text{Cost}/10^6 \text{ kw} = \text{Rs. } 250 \times 10^7/10^6 \text{ kw.}$$

Assuming a uniform expenditure over 6 years of installation period, and, a time horizon of another 64 years, the annual capital cost recovery for hydropower works out to be $0.001296 \times 10^7/10^6$ kwhr.

(f) Operation, maintenance and replacement (OMR) cost:

OMR cost is assumed as Rs. 25/kw installed, i.e., Rs. $2.5 \times 10^7/10^6$ kw or $0.0002854 \times 10^7/10^6$ kwhr.

(g) Energy benefit:

The rate of development of energy for Bargi dam is shown in Figure 4.4.2. Using a discount rate of 5%, and, a development period as shown in the figure, the annual benefit from sale of energy at a rate of Rs. 0.50/kwhr comes to Rs. $0.0328 \times 10^7/10^6$ kwhr.

Thus for Bargi project, it is seen that the annual gross benefit from irrigation is Rs. 5.5460×10^7/MAF, annual cost for irrigation Rs. 1.2672×10^7/MAF, OMR cost for irrigation

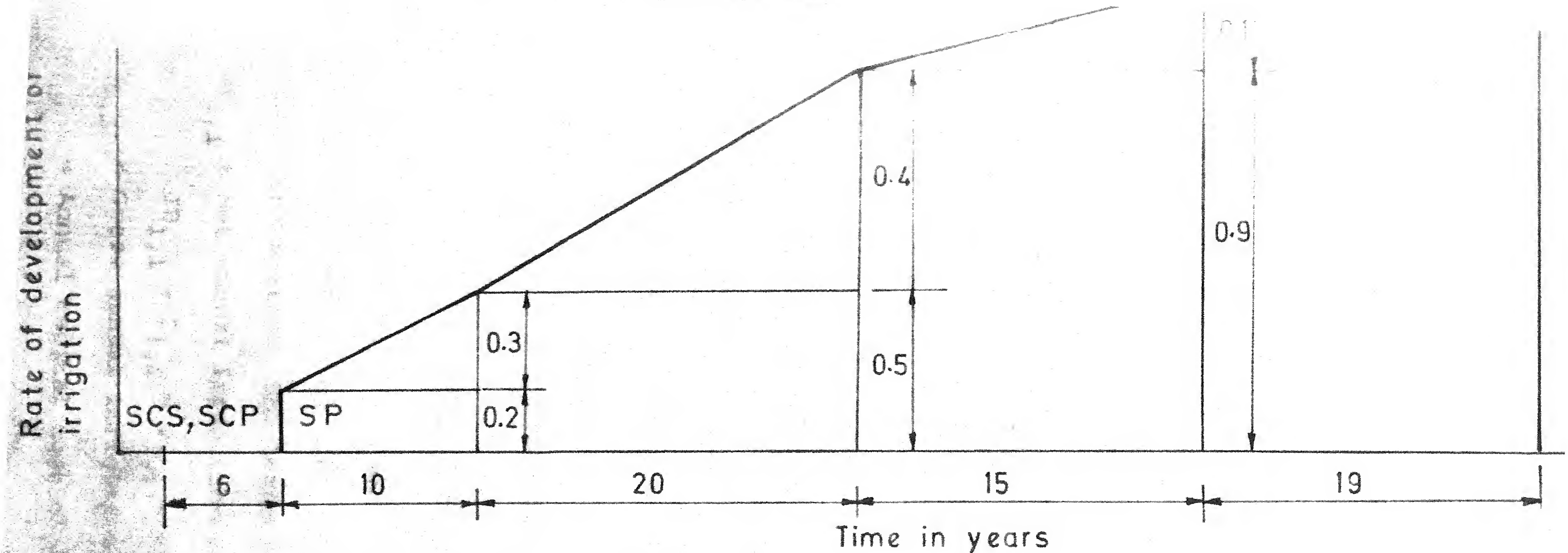
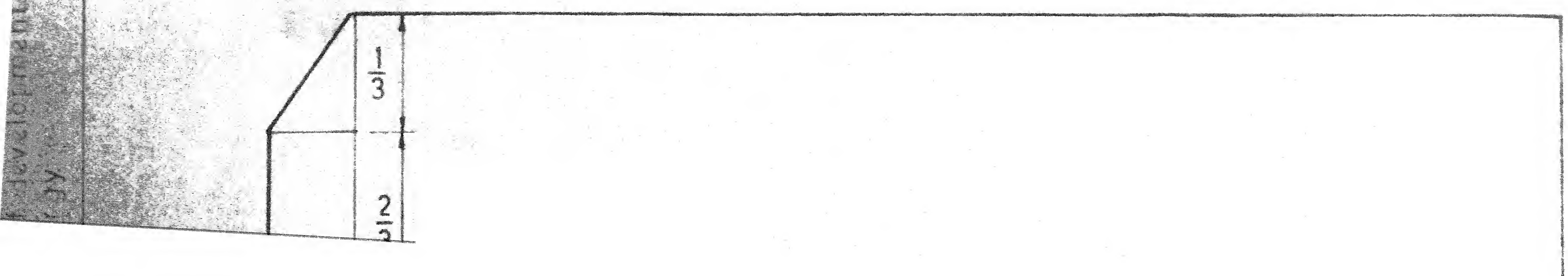


FIG. 4.4.1 RATE OF IRRIGATION DEVELOPMENT

SCS = Starting of construction of system
SCP = " " " " project
SP = " " production



Rs. 0.1734 x 10^7/MAF and annualized reservoir cost Rs. 1.51 x 10^7/MAF. Also gross annual benefits from power is Rs. 0.0328 x $10^7/10^6$ kwhr, annual cost of power generation Rs. 0.001296 x $10^7/10^6$ kwhr and OMR cost for power Rs. 0.0002854 x $10^7/10^6$ kwhr. Using each of these unit costs and benefits as a guide, cost-capacity curves, gross benefit curves, OMR cost curves, etc. are prepared and shown in Figures 4.4.3 to 4.4.9 for Bargi project. Cost and benefit functions for each project are tabulated in Tables 4.4.1 to 4.4.5. The net benefit function for irrigation for Bargi project is developed and is shown in Figure 4.4.10. Similarly for net benefit function for energy for Bargi project is developed and is shown in Fig. 4.4.11. For other projects, detailed calculations, and curves such as cost-capacity, gross benefit curves, OMR cost curves and net benefit curves are given in Appendix.

4.5. Mathematical Formulation of LPD Model

The objective of the problem is to maximize the net annual benefits from irrigation and energy for the whole system

$$\text{Maximize } B = \sum_{i=1}^{5} INB_{1,i} + ENB_{2,i} - C_{3,i} \tag{4.2}$$

The first subscript, 1, 2 and 3 represent irrigation, energy and reservoir respectively. The second subscript i, represents a site in the system. The terms used in the objective function are

$INB_{1,i}$ = Net annual irrigation benefit at site i and is equal to $IB_{1,i} - C_{1,i} - O_{1,i}$ where;

$IB_{1,i}$ = Gross annual irrigation benefit at site i;

$C_{1,i}$ = Annual capital cost of irrigation works at site i;

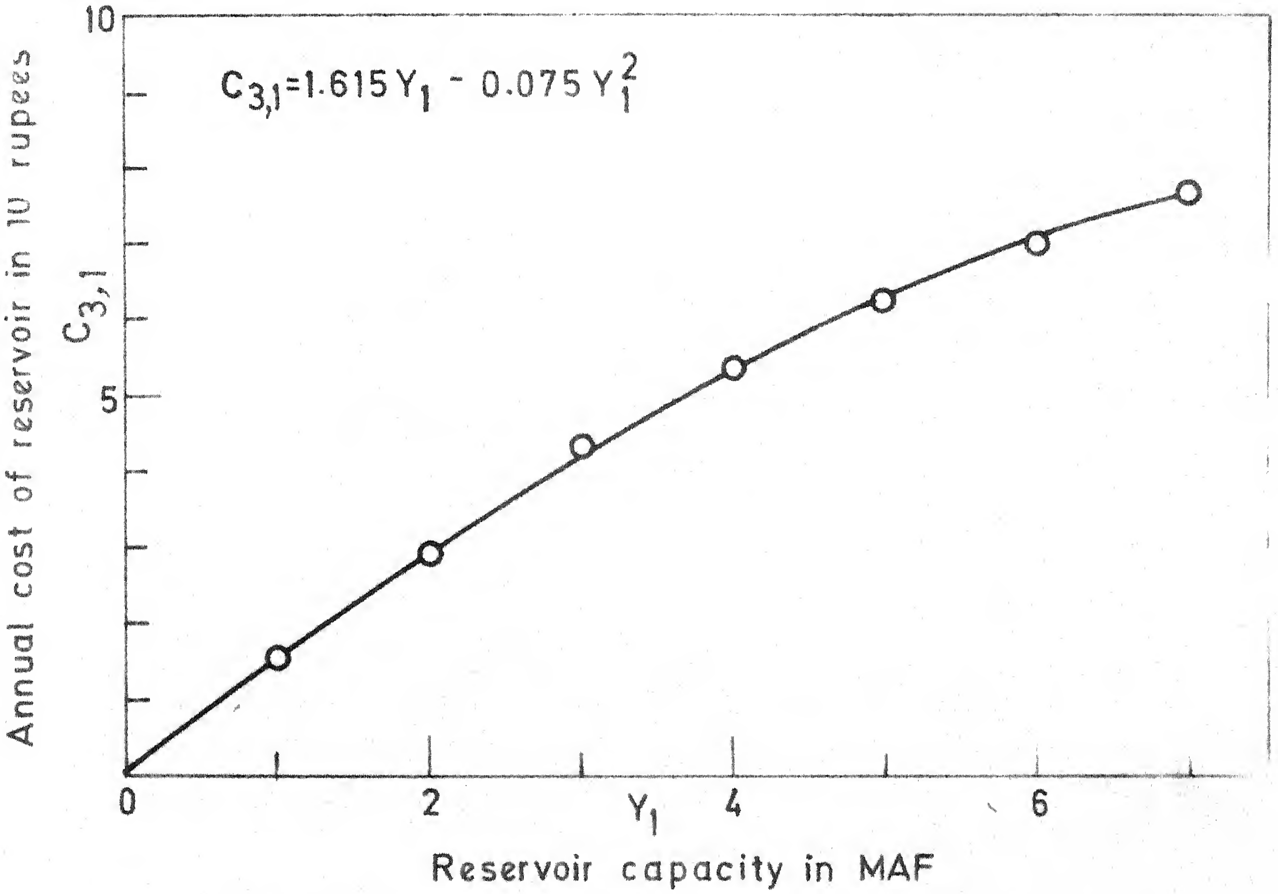


FIG. 4.4.3 ANNUAL COST OF BARGI RESERVOIR

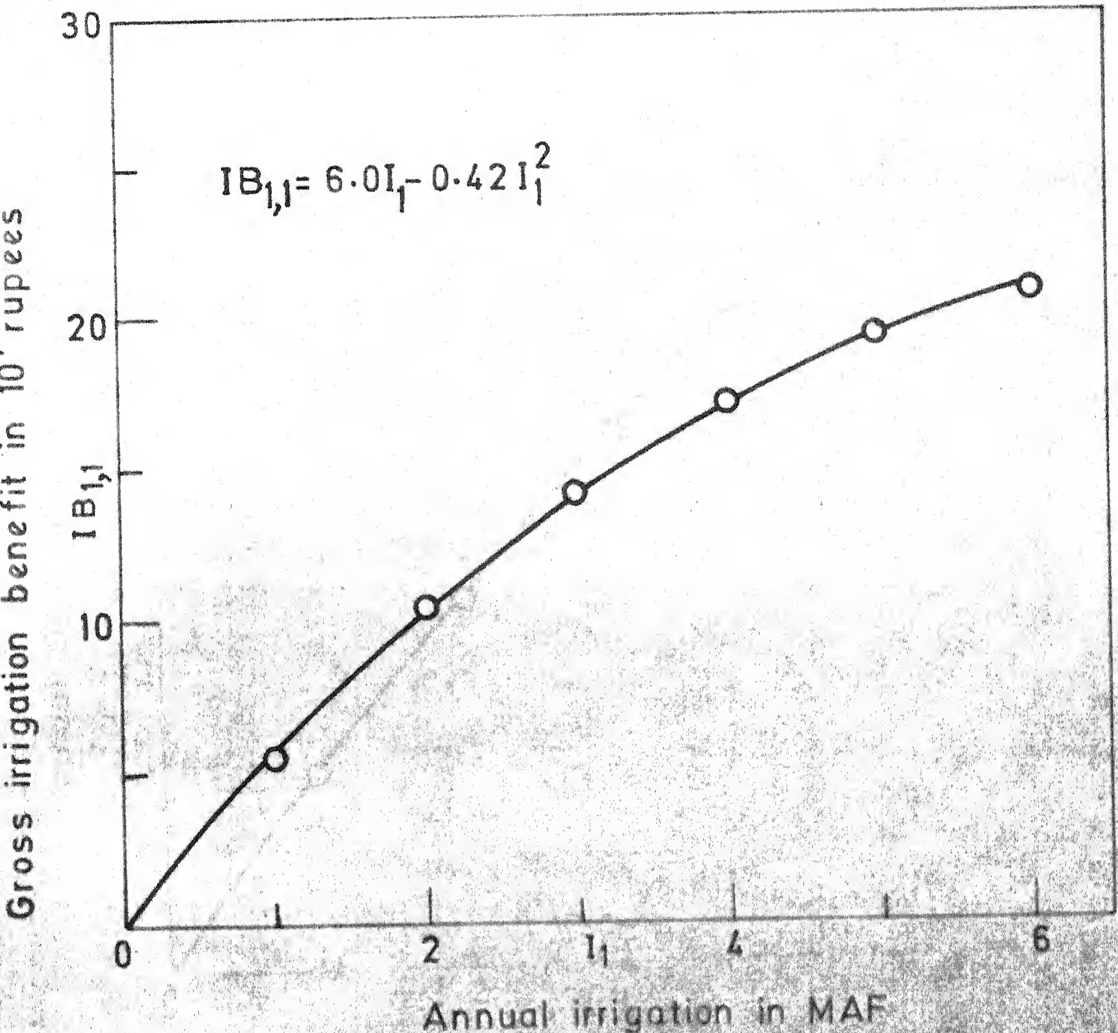


FIG.4.4.4 ANNUAL GROSS BENEFIT FROM IRRIGATION FOR BARGI RESERVOIR

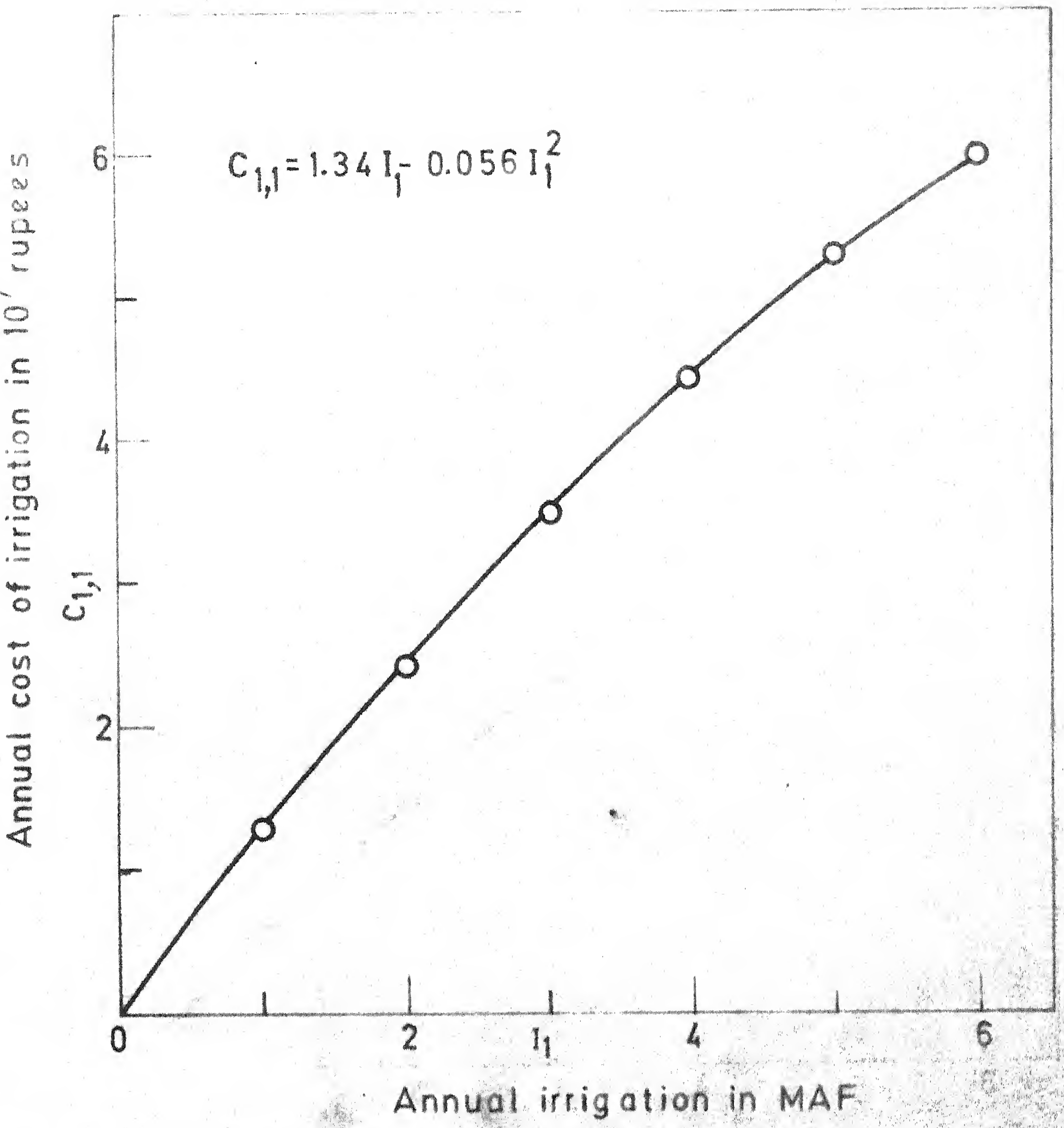


FIG. 4.4.5 ANNUAL COST OF IRRIGATION, DIVERSION AND DISTRIBUTION WORKS FOR BARGI RESERVOIR

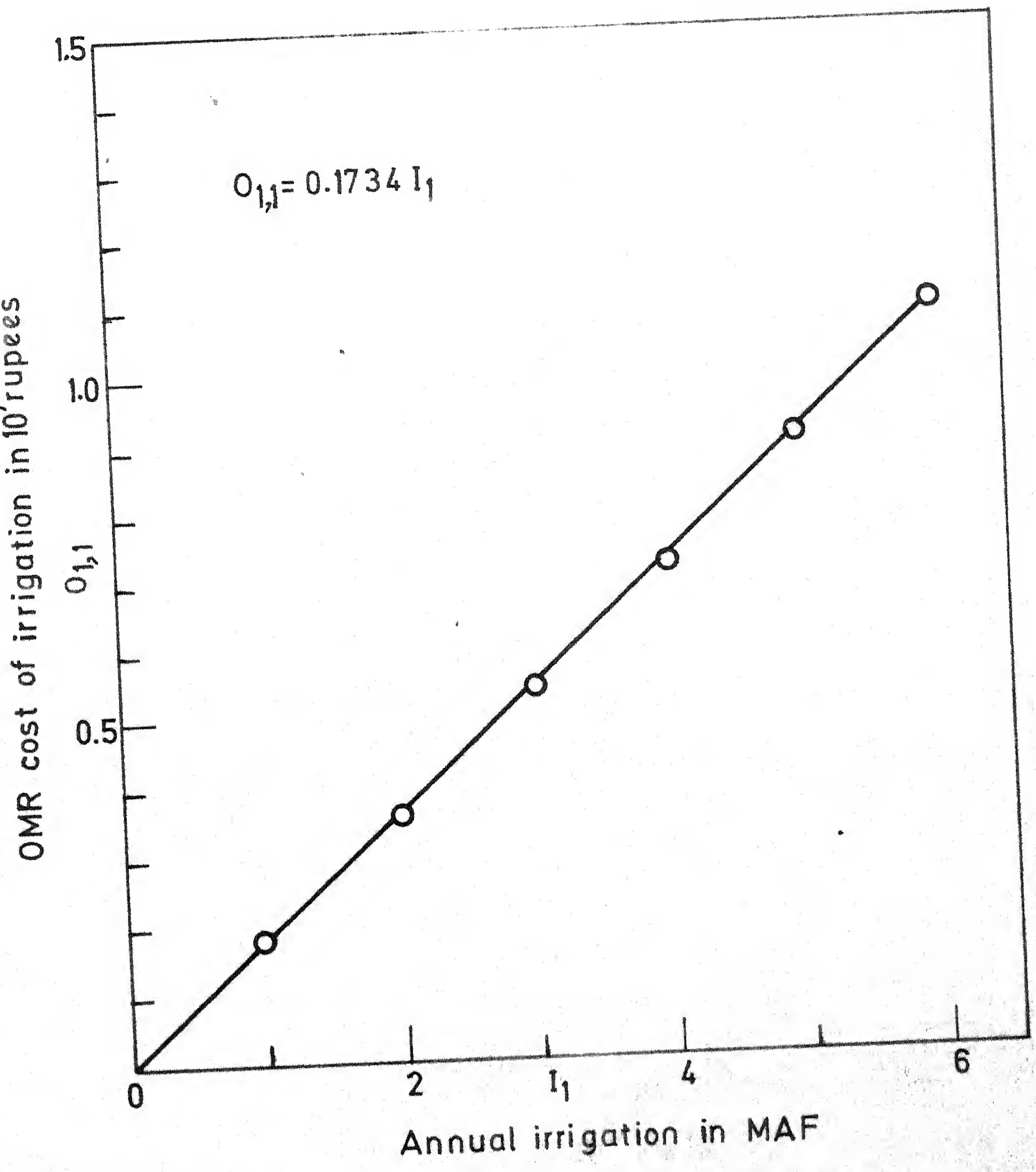


FIG. 4.4.6 OMR COST OF IRRIGATION, DIVERSION AND DISTRIBUTION WORKS FOR BARGI RESERVOIR

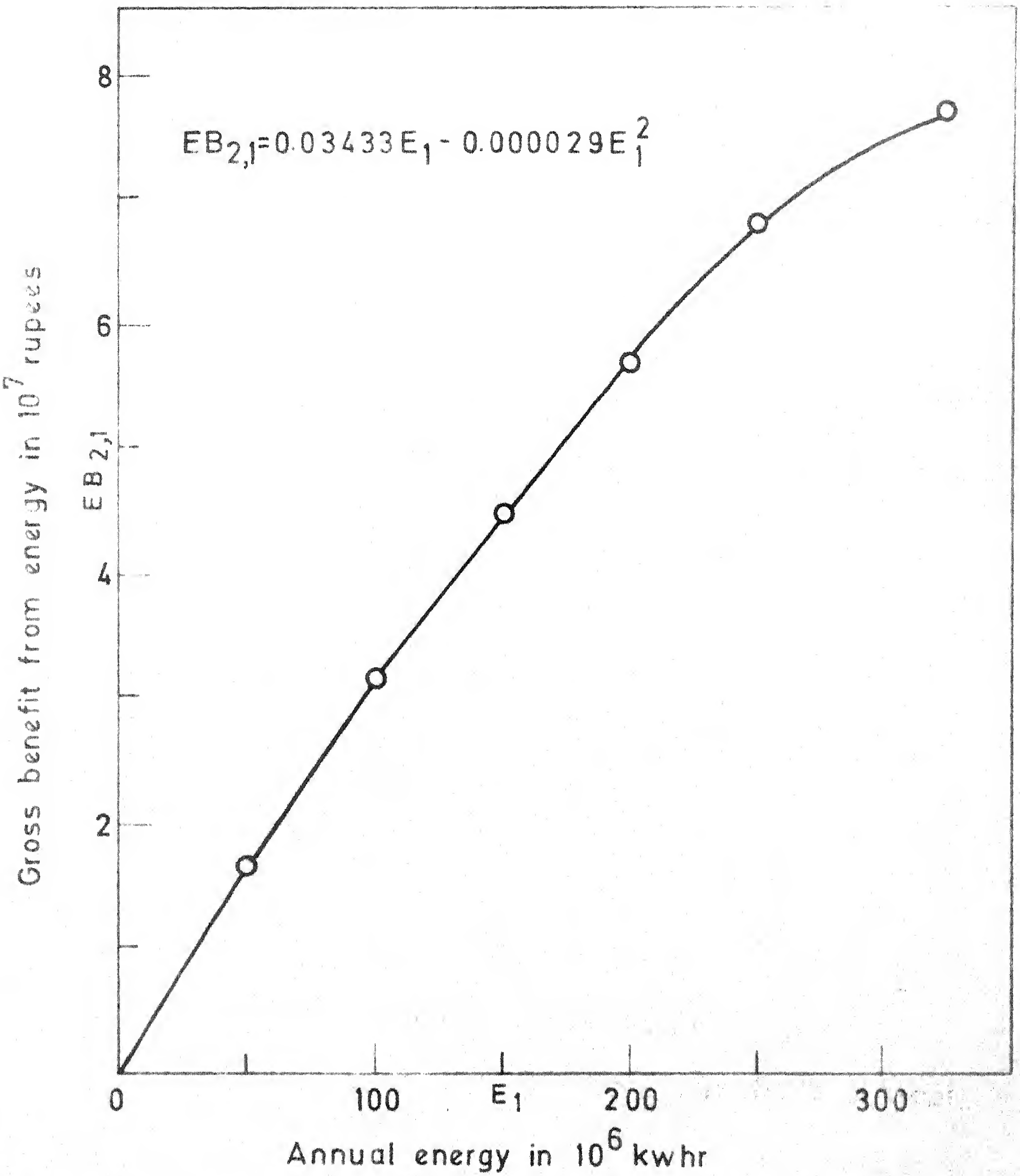


FIG. 4.4.7 ANNUAL GROSS BENEFIT FROM ENERGY FOR BARGI RESERVOIR

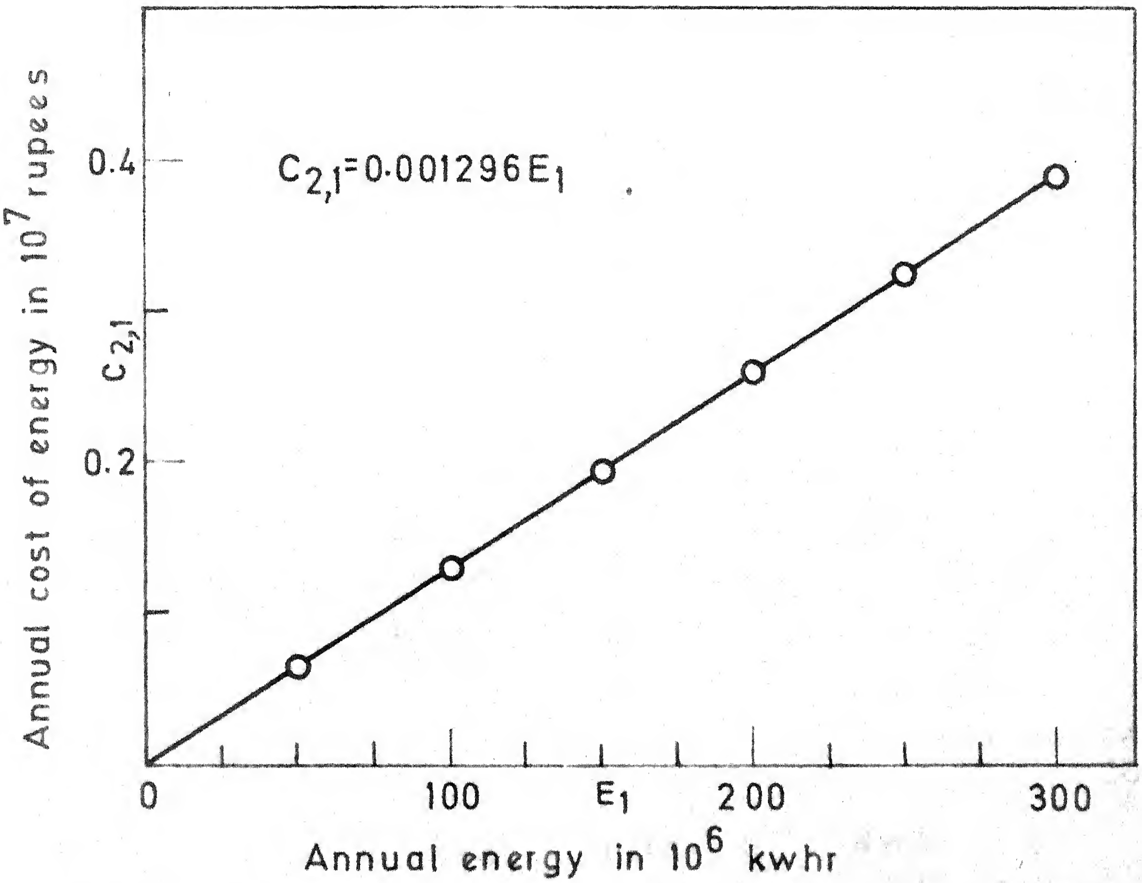


FIG. 4.4.8 ANNUAL COST OF ENERGY FOR BARGI RESERVOIR

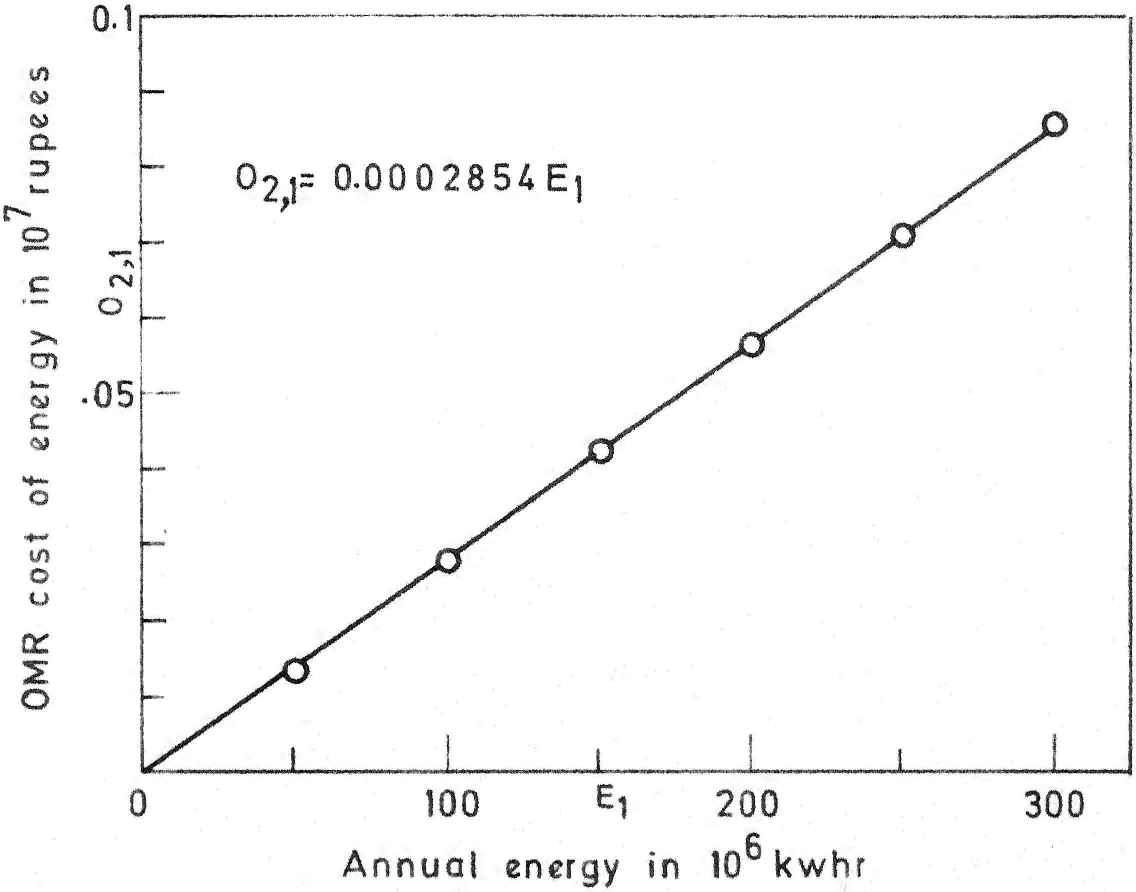


FIG.4.4.9 OMR COST OF ENERGY FOR BARGI RESERVOIR

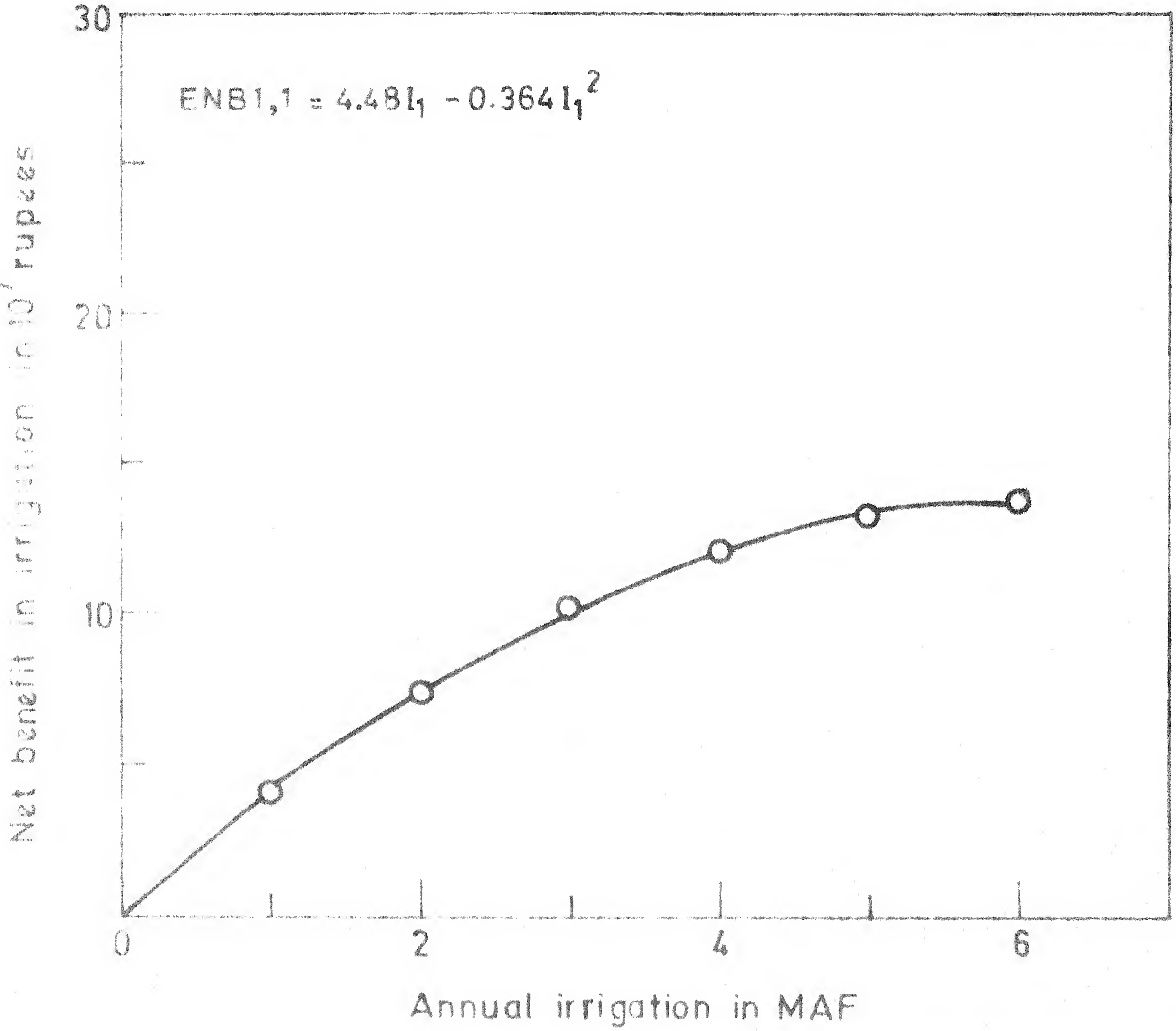


FIG. 4.4.10 ANNUAL NET BENEFIT FROM IRRIGATION FOR BARGI RESERVOIR

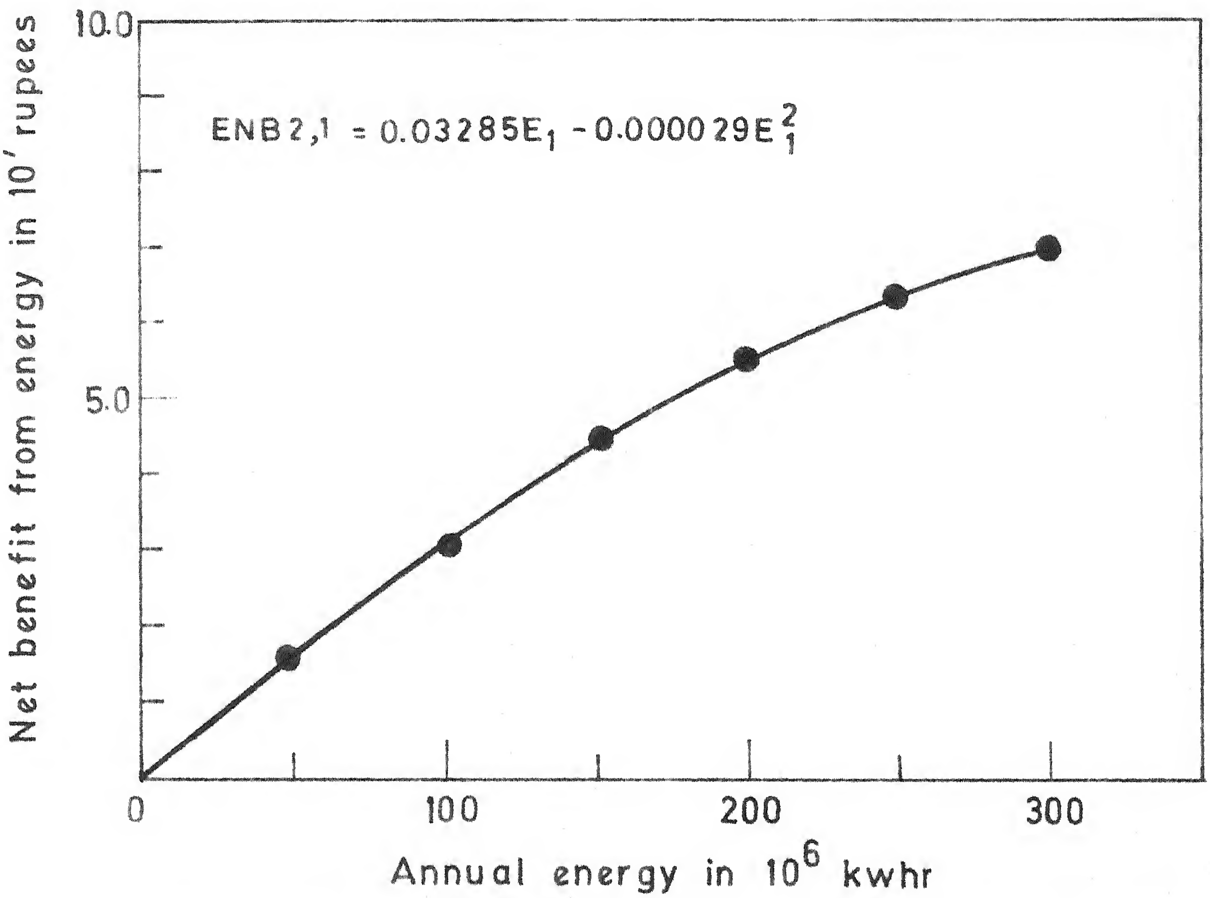


FIG. 4.4.11 ANNUAL NET BENEFIT FROM ENERGY FOR BARGI RESERVOIR

TABLE 4.4.1. COST AND BENEFIT FUNCTIONS

BARGI

Sl. No.	Independent variable	Dependent variable	Functional relationship
1	Reservoir capacity (MAF)	Capital cost in crores	$C_{3,1} = 1.615\ Y_1 - 0.073\ Y_1^2$
2	Reservoir capacity (MAF)	OMR cost in crores	$O_{3,1} = 0.000$
3	Annual target output for irrigation (MAF)	Gross irrigation benefit in crores	$IB_{1,1} = 6.0I_1 - 0.42I_1^2$
4	Annual target for irrigation (MAF)	Capital cost of irrigation in crores	$C_{1,1} = 1.34I_1 - 0.056I_1^2$
5	Annual target for irrigation (MAF)	OMR cost in crores	$O_{1,1} = 0.1734I_1$
6	Annual target for energy (10^6 kwhr)	Gross energy benefits in crores	$EB_{2,1} = 0.03433E_1 - 0.000029E_1^2$
7	Annual target for energy (10^6 kwhr)	Capital cost in crores	$C_{2,1} = 0.001296E_1$
8	Annual target for energy (10^6 kwhr)	OMR cost in crores	$O_{2,1} = 0.0002854E_1$

Note: 1 crore = 10^7.

TABLE 4.4.2. COST AND BENEFIT FUNCTIONS

NARMADASAGAR

Sl. No.	Independent variable	Dependent variable	Functional relationship
1	Reservoir capacity (MAF)	Capital cost in crores	$C_{3,2} = 0.486\ Y_2 - 0.0138\ Y_2^2$
2	Reservoir capacity (MAF)	OMR cost in crores	$O_{3,2} = 0.000$
3	Annual irrigation target output (MAF)	Gross benefit from irrigation in crores	$IB_{1,2} = 3.9I_2 - 0.146I_2^2$
4	Annual irrigation target output (MAF)	Capital cost in crores	$C_{1,2} = 1.19I_2 - 0.026I_2^2$
5	Annual irrigation target output (MAF)	OMR cost in crores	$O_{1,2} = 0.20I_2$
6	Annual energy target outputs (10^6 kwhr)	Gross benefit from energy in crores	$EB_{2,2} = 0.03075E_2 - 0.0000039E$
7	Annual energy target output (10^6 kwhr)	Capital cost in crores	$C_{2,2} = 0.00155E_2$
8	Annual energy target output (10^6 kwhr)	OMR cost in crores	$O_{2,2} = 0.00039E_2$

Note: 1 crore = 10^7.

TABLE 4.4.3. COST AND BENEFIT FUNCTIONS

OMKARESHWAR

Sl. No.	Independent variable	Dependent variable	Functional relationship
1	Reservoir capacity (MAF)	Capital cost in crores	$C_{3,3} = 2.083Y_3 - 0.555Y_3^2$
2	Reservoir capacity (MAF)	OMR cost in crores	$O_{3,3} = 0.000$
3	Annual irrigation target output (MAF)	Gross benefit from irrigation in crores	$IB_{1,3} = 2.735I_3 - 0.0814I_3^2$
4	Annual irrigation target output (MAF)	Capital cost in crores	$C_{1,3} = 0.955I_3 - 0.0304I_3^2$
5	Annual irrigation target output (MAF)	OMR cost in crores	$O_{1,3} = 0.35I_3$
6	Annual energy target output (10^6 kwhr)	Gross benefit from energy in crores	$EB_{2,3} = 0.02115E_3 - 0.0000047E_3^2$
7	Annual energy target output (10^6 kwhr)	Capital cost in crores	$C_{2,3} = 0.00099E_3$
8	Annual energy target output (10^6 kwhr)	OMR cost in crores	$O_{2,3} = 0.00040E_3$

Note: 1 crore = 10^7.

TABLE 4.4.4. COST AND BENEFIT FUNCTIONS

MAHESHWAR

Sl. No.	Independent variable	Dependent variable	Functional relationship
1	Reservoir capacity (MAF)	Capital cost in crores	$C_{3,4} = 4.528Y_4 - 5.16Y_4^2$
2	Reservoir capacity (MAF)	OMR cost in crores	$O_{3,4} = 0.000$
3	Annual energy target output (10^6 kwhr)	Gross benefit from energy in crores	$EB_{2,4} = 0.02437E_4 - 0.0000089E_4^2$
4	Annual energy target output (10^6 kwhr)	Capital cost in crores	$C_{2,4} = 0.001455E_4$
5	Annual energy target output (10^6 kwhr)	OMR cost in crores	$O_{2,4} = 0.00059E_4$

Note: 1 crore = 10^7.

TABLE 4.4.5. COST AND BENEFIT FUNCTIONS

SARDAR SAROVAR

Sl. No.	Independent variable	Dependent variable	Functional relationship
1	Reservoir capacity (MAF)	Capital cost in crores	$C_{3,5} = 1.074Y_5 - 0.04Y_5^2$
2	Reservoir capacity (MAF)	OMR cost in crores	$O_{3,5} = 0.000$
3	Annual irrigation target output (MAF)	Gross benefit from irrigation in crores	$IB_{1,5} = 5.964I_5 - 0.2628I_5^2$
4	Annual irrigation target output (MAF)	Capital cost in crores	$C_{1,5} = 1.220I_5 - 0.050I_5^2$
5	Annual irrigation target output (MAF)	OMR cost in crores	$O_{1,5} = 0.29I_5$
6	Annual energy target output (10^6 kwhr)	Gross benefit from energy in crores	$EB_{2,5} = 0.0193E_5 - 0.0000021E_5^2$
7	Annual energy target output (10^6 kwhr)	Capital cost in crores	$C_{2,5} = 0.00105E_5$
8	Annual energy target output (10^6 kwhr)	OMR cost in crores	$O_{2,5} = 0.00026E_5$

Note: 1 crore = 10^7.

$O_{1,i}$ = Annual OMR cost of irrigation work at site i;

$ENB_{2,i}$ = Net annual energy benefit at site i and is equal to $EB_{2,i} - C_{2,i} - O_{2,i}$ where;

$EB_{2,i}$ = Gross annual energy benefit at site i;

$C_{2,i}$ = Annual capital cost of energy at site i;

$O_{2,i}$ = Annual OMR cost of energy generation at site i;

$C_{3,i}$ = Annual capital cost of reservoir at site i;

Y_i = Gross storage capacity of reservoir at site i.

Substituting for the variables in the objective function, the following expression is obtained:

$$
\begin{aligned}
B = {} & 4.48\ I_1 - 0.364\ I_1^2 + 0.03288\ E_1 - 0.000029\ E_1^2 \\
& - (1.615\ Y_1 - 0.073\ Y_1^2) + 2.51\ I_2 - 0.12\ I_2^2 + 0.0288\ E_2 \\
& - 0.0000039\ E_2^2 - (0.486\ Y_2 - 0.0138\ Y_2^2) + 1.43\ I_3 \\
& - 0.051\ I_3^2 + 0.01976\ E_3 - 0.0000047\ E_3^2 - (2.083\ Y_3 \\
& - 0.555\ Y_3^2) + 0.02232\ E_4 - 0.0000089\ E_4^2 - (4.528\ Y_4 \\
& - 5.16\ Y_4^2) + 4.445\ I_5 - 0.2128\ I_5^2 + 0.018\ E_5 \\
& - 0.0000021\ E_5^2 - (1.074\ Y_5 - 0.040\ Y_5^2)
\end{aligned}
\tag{4.3}
$$

The optimization of the objective function is subject to the following constraints;

(a) The volume of water released from reservoir must be sufficient to meet irrigation demands of that period from that reservoir, i.e.,

$$a_{i,t} \geq K_{i,t} I_i \qquad \forall_{i,t} \tag{4.4}$$

where $a_{i,t}$ is the water released from the reservoir i in time t, and $K_{i,t}$ is the proportion of irrigation demand I_i to be diverted for irrigation in time t, from site i;

(b) The volume of water released during any period cannot exceed the contents of the reservoir at the beginning of the period plus flow into the reservoir during the period, i.e.,

$$a_{i,t} + c_{i,t} \leq ST_{i,t} + f_{i,t} + a_{i-1,t} - K_{i-1,t} I_i + K'_{i-1,t} I_i + c_{i-1,t} \qquad \forall_{i,t} \tag{4.5}$$

where $c_{i,t}$ is the volume of water released through river-bed turbine in time t at reservoir site i;

(c) The contents of the reservoir at the beginning of any period cannot exceed the quantity left over from the previous period, i.e.;

$$ST_{i,t+1} \leq ST_{i,t} + f_{i,t} + a_{i-1,t} + c_{i-1,t} - K_{i-1,t} I_i + K'_{i-1,t} I_i - a_{i,t} - c_{i,t} \qquad \forall_{i,t} \tag{4.6}$$

(d) **The** contents of reservoir at any period cannot exceed the capacity of reservoir

$$ST_{i,t} \leq Y_i \qquad \forall_{i,t} \tag{4.7}$$

where $ST_{i,t}$ is storage in reservoir i at the beginning of period t;

(e) The flow through the turbines should meet energy generation demand. Variation in generation efficiency at different sites is neglected at this stage;

$$\delta_t E_i - (1.025)(e)(h_i)(a_{i,t}) \leq 0 \qquad \forall_{i,t} \quad \text{(for canal power house)}$$

$$\delta_t E_i - (1.025)(e)(h_i)(C_{i,t}) \leq 0 \qquad \forall_{i,t} \quad \text{(for river bed power house)}$$

(4.8)

where 1.025 is the conversion factor of MAF to 10^6 kwhr, e is the turbine and generator efficiency, and, h_i, is the average head on turbine at site i.

A few more constraints were added on the basis of some design criteria as listed below:

(f) It has been recommended by the Tribunal that the total water used by Madhya Pradesh should be atleast 1.947 times the amount used by Gujarat, i.e.,

$$\sum_{i=1}^{4} I_i \geq 1.947\, I_5 \qquad (4.9)$$

(g) The total energy produced should be atleast equal to 4100×10^6 kwhr, i.e.

$$\sum_{i=1}^{5} E_i \geq 4100 \qquad (4.10)$$

(h) The dead storage of a reservoir puts a lower limit on the reservoir storage in the case of reservoir producing power, i.e.,

$$ST_{i,t} \geq D_i \qquad (4.11)$$

where D_i is the dead storage capacity of reservoir i.

(i) The Full Supply Reservoir Level (FRL) is fixed at +455 ft for the terminal reservoir (Sardar Sarovar) by the Tribunal. The gross storage at this level is 7.75 MAF, i.e.,

$$Y_5 = 7.75 \tag{4.12}$$

The return flow is taken as 10% of the annual water used in the upstream. Evaporation losses and flood storages are not considered in the LPD model. Deterministic streamflows are used in this model.

An illustration of application of the above constraints to, say, Sardar Sarovar is given by the following equations:

$$- a_{5,1} + 0.1934\ I_5 \leq 0$$

$$- a_{5,2} + 0.3490\ I_5 \leq 0$$

$$- a_{5,3} + 0.2931\ I_5 \leq 0$$

$$- a_{5,4} + 0.1645\ I_5 \leq 0$$

$$a_{5,1} + ST_{5,1} - c_{4,1} \leq 3.224$$

$$a_{5,2} + ST_{5,2} - c_{4,2} \leq 0.625$$

$$a_{5,3} + ST_{5,3} - c_{4,3} \leq 0.055$$

$$a_{5,4} + ST_{5,4} - c_{4,4} \leq 0.203$$

$$a_{5,1} + ST_{5,2} - ST_{5,1} - c_{4,1} \leq 3.224$$

$$a_{5,2} + ST_{5,3} - ST_{5,2} - c_{4,2} \leq 0.625$$

$$a_{5,3} + ST_{5,4} - ST_{5,3} - c_{4,3} \leq 0.055$$

$$a_{5,4} + ST_{5,1} - ST_{5,4} - c_{4,4} \leq 0.203$$

$$ST_{5,1} - Y_5 \leq 0$$

$$ST_{5,2} - Y_5 \leq 0$$

$$ST_{5,3} - Y_5 \leq 0$$

$$ST_{5,4} - Y_5 \leq 0$$

$$-83.64\ a_{5,1} + 0.24\ E_5 \leq 0$$

$$-83.64\ a_{5,2} + 0.28\ E_5 \leq 0$$

$$-83.64\ a_{5,3} + 0.27\ E_5 \leq 0$$

$$-83.64\ a_{5,4} + 0.21\ E_5 \leq 0$$

$$I_1 + I_2 + I_3 + OI_4 \geq 1.947\ I_5$$

$$E_1 + E_2 + E_3 + E_4 + E_5 \geq 4100$$

$$ST_{5,1} \geq 2.97$$

$$ST_{5,2} \geq 2.97$$

$$ST_{5,3} \geq 2.97$$

$$ST_{5,4} \geq 2.97$$

$$Y_5 = 7.75 \tag{4.13}$$

4.6. Method of Solution

The objective is to find the values of variables a_t, c_t, ST_t, I, Y, E for each reservoir, that maximize the objective function subject to the constraints mentioned above. The constraint equation (4.8) is nonlinear because head is the function of storage which is variable quantity. Energy production is the function of the product of the head on the turbine and discharge passing through turbine. It is made linear by considering average head on turbine.

The objective function is also nonlinear. However it is seen that this nonlinearity is of special kind namely it is sum of several nonlinear functions each of which is a function of one variable only. Such nonlinearities can be handled by the separable linear programming technique. In this technique each nonlinear function is replaced by a piece-wise linear function. The resulting expression will be linear and can be solved by the familiar linear programming technique.

It is well known that linear programming can be used generally to maximize concave functions or minimize convex functions. If the nonlinear concave or convex functions are relatively smooth the global optimum solution results. If not there is a possibility of getting multiple optima (Loucks, 1981, page 58).

CHAPTER 5

SIMULATION

5.1. Introduction

Simulation attempts to study the performance of a system and examines consequent economic effect of the system by a computerized algorithm. Simulation models are more popular due to their simplicity and versatility. They are widely used in the discipline of science and technology. Simulation studies a complex system which cannot be analyzed by the use of analytical methodologies. Simulation studies have been greatly facilitated by the advent of high speed computers. The economic response of the various alternatives can be examined, if economic data for each project and other activity in the basin can be identified well in advance. Nonlinear, dynamic, and stochastic response of the system can be incorporated in the simulation program.

A major difficulty with simulation technique is to develop a simulation program. Debugging and testing of the program are the other difficulties associated with it. A large amount of input and output data to be handled during the execution is also a difficulty, one has to face.

A simulation model is time sequenced. Weekly, ten-daily, or monthly simulation study is adopted depending on the type of problem and information required from it. For flood simulation, the time is reduced to 6-hours or 3-hours. Many assumptions are made while developing a simulation program.

For larger time interval some of the approximations are invalid and thus the simulation results become unreliable.

There are three main limitations to simulation approach. It does not yield a unique optimal solution. It gives a large set of alternative design variables. It is a tedious job to examine such large sets. To overcome these difficulties partly, sampling methods for efficient selection of combination of variables are used. A second limitation of simulation results from the lack of flexibility in operating procedure of the system. This can be overcome partly, by using flexible operating rules. The third limitation of simulation derives from the use of historical streamflow record. This can be overcome by using synthetic streamflows.

In the present study, the sampling method used to explore the response surface is the steepest ascent method. The flexibility introduced in the operating policy is in the form of modification in the release policy according to the hydrological classification of the basin as very wet, wet, average, and, dry year. This is discussed later in Section 5.4

As reported in Chapter 4 the system under study consists of five reservoirs. Out of these, four reservoirs (Bargi, Narmadasagar, Omkareshwar, Sardar Sarovar) have three design variables namely irrigation quantity, reservoir capacity, and energy. The remaining one (Maheshwar) has two, namely reservoir capacity and energy. Thus there are 14 variables. The net benefits to simulating combinations of these 14 variables in the Narmada basin under study, creates a 14-dimensional response surface, that includes atleast one point with the

highest net benefits. Even if we assume a coarse grid of 5 divisions for each variable it would be required to examine $5^{14} \approx 6 \times 10^9$ combinations. The only practical solution to find the optimal combination out of these 14 variables is to use a suitable method of sampling the variables to explore the net benefit response surface.

5.2. Sampling Methods

5.2.1. Types of methods

There are five methods for exploring the response surface (Maass, et al., 1962):

(a) Uniform grid method

(b) Random sampling

(c) Single factor

(d) Marginal analysis

(e) Steepest ascent method.

(a) Uniform grid method: In this method each of the n variables is divided into m equal increments. Net benefits are simulated for each of m^n points on the resulting uniform grid. The point on the surface with the highest net benefit is selected. The advantage of this method is its ability to map the entire response surface of the system with small number of variables. The main disadvantage of this method is that it spends more time in examining areas of low net benefit compared to search the higher areas for the peak.

(b) Random sampling: Random values of variables are picked up from its population, and net benefits for the resulting point

on the response surface are selected. This method is capable of handling large number of decision variables.

(c) Single factor method: Initial values are selected for the variables. The values of all variables except one, say the first one, are held constant, and the value of the first variable is altered until the maximum net benefit is attained. This process is repeated with a second variable and so on. This method works best when the variables are independent of one another. The decision variables are interrelated particularly for water resource system, hence this method is inherently unsuitable to water resource systems.

(d) Sampling by incremental or marginal analysis: In this method two variables are altered at a time, while remaining variables are held constant. The relationship between the variables is isolated. It provides the information regarding the direction in which the change should be made. This method is most suitable when there are few variables. The important pairs are identified by prior analysis.

(e) Steepest ascent method: This is an iterative method. Sampling moves sequentially from lower to higher elevation on the response surface. The starting points X_i^o are selected on the basis of information available from preliminary design. Each variable is incremented, keeping other variables constant, by preselected amount Δx_i. The change in benefit value ΔB_i is calculated for each variable. The associated change in net benefits ΔB_i and its rate of change, $\Delta B_i/\Delta X_i$ are computed. A move is calculated from the starting values X_i^o to the first

revised base values X_i^1. It requires that the change in each variable be made proportional to the associated rate of improvement $\Delta B_i/\Delta X_i$. The move to the new base is symbolized by the equation;

$$X_i^1 - X_i^o = C_5(\Delta B_i/\Delta X_i) \tag{5.1}$$

where C_5 is the proportionality constant. The relationship between the distance 'd' from the original base to the revised base is symbolized by the equation;

$$C_5 = d/[\sum_1^n (\Delta B_i/\Delta X_i)^2]^{1/2} \tag{5.2}$$

Alternatively C_5 can be determined as below (Maass, et al., 1962). C_5 can be of such magnitude that the maximum absolute value of change for any variable will equal a specified magnitude K_5 or max $X_i^1 - X_i^o = K_5$, and it follows from equation (5.2) that

$$C_5 \max |\Delta B_i/\Delta X_i| = K_5$$

$$K_5/\max |\Delta B_i/\Delta X_i| \leq K_5/|\Delta B_i/\Delta X_i|$$

$$C_5 \leq K_5 |\Delta X_i/\Delta B_i| \quad \text{or}$$

$$C_5 = K_5 \min |\Delta X_i/\Delta B_i| \tag{5.3}$$

The routine of calculations is repeated until there is no further improvement. To use this method, the variables must have same units. This is not possible in water resource system. To overcome this difficulty, the units of the system components as well as sampling parameters d and K_5 are made dimensionless by expressing them as ratios of their permissible range.

The major advantages of steepest ascent method is that it measures combined influence of variables on the net benefits of the system in each lift. The major disadvantage is that it may miss true summit on a response surface.

5.2.2. Application of steepest ascent method to the system under study

A computer program is developed for the steepest ascent method to suit the requirements of the present system. The range of variables in natural units are selected on the basis of the information obtained from the results of LPD model. The size of the step for each variable is set at about one fifth of its range. The objective function developed for the LPD model is used to represent response surface. A set of design variables is selected arbitrarily as starting base values. The net benefit for this starting set is calculated. Each variable is then incremented, keeping other variables constant. The change in the benefit value ΔB_i due to incrementing each variable is calculated. The step value ΔX_i in natural unit is converted into range unit for each variable. The ratio, $\Delta X_i / \Delta B_i$ is calculated for each variable. An absolute minimum value out of these ratios is found. The value of C_5 is calculated as the product of absolute minimum value X20. The move from original base to new base is equal to $C_5/(\Delta X_i / \Delta B_i)$, which is then converted to natural units for each variable. A second base = original base + move. The revised net benefit is calculated. It is then compared with the net benefit already calculated for the starting base. If the value is positive then the procedure is repeated, considering

the second base as the original base. The procedure is repeated until no improvement is found in the benefit value. It is found that it takes about 7 iterations for this phase. A second sample is taken and similar computations made. Results of 9 such samples are given in the next chapter, Tables 6.3.1 to 6.3.9. Based on these tabular values the final selected set is shown in Table 6.3.10.

5.3. Data for Simulation

Narmada river basin as modeled has five reservoirs: (i) Bargi (ii) Narmadasagar, (iii) Omkareshwar, (iv) Maheshwar and (v) Sardar Sarovar. Four serve two purposes namely irrigation and power. One reservoir namely Maheshwar is a hydropower project. Canal head power houses (CHPH) are provided at reservoir sites (i), and (v). River bed power houses (RBPH) are provided at the remaining reservoir sites.

In the present study two aspects are considered in the simulation study: (a) monthly simulation, (b) 3-hourly flood simulation. Monthly simulation study is carried out for conservation purposes, i.e., reservoirs are filled up during monsoon period (filling period) and stored water is used to meet the demand during nonmonsoon period (depletion period). Monthly discharge data at each reservoir site are given in Tables 3.4.10 to 3.4.14.3-hourly flow data for the four selected floods for selected reservoir sites are given in Tables 3.4.18 to 3.4.25. The types of flood classification on the basis of monthly mean flow and trigger value are given in Tables 5.3.1 to 5.3.4. The release policy during flood month based on

TABLE 5.3.1. TYPE OF FLOODS AND RANGE FOR SELECTION

Narmadasagar (NS)

Trigger value (TRY) = 155000 cfs

Sl. No.	Year	Month	Date of peak	Flood peak (cfs)	Flood month mean monthly flow at		Range excess over TRY	Actual excess value at NS	Flood type
					Mortakka	NS			
1	1959	Sept	15	971385	225141	205325	0-30000	50325	1
2	1961	Sept	17	1191020	362255	330606	30001-85000	175606	2
3	1970	Sept	6	1366240	270112	246727	85001-165000	91727	3
4	1975	Sept	13	1029350	172187	156126	> 165001	1126	4

TABLE 5.3.2. TYPE OF FLOODS AND RANGE FOR SELECTION

Omkareshwar (OMK)

Trigger value (TRY) = 163000 cfs

Sl. No.	Year	Month	Date of peak	Flood peak (cfs)	Flood month mean monthly flow at		Range excess over TRY	Actual excess value at OMK	Flood type
					Mortakka	OMK			
1	1959	Sept	15	971385	225141	216889	0-30000	53889	1
2	1961	Sept	17	1191020	362255	349076	30001-85000	186076	2
3	1970	Sept	6	1366240	270112	260374	85001-165000	97374	3
4	1975	Sept	13	1029350	172187	165498	>165000	2498	4

TABLE 5.3.3. TYPE OF FLOODS AND RANGE FOR SELECTION

Maheshwar (MAH)

Trigger value (TRY) = 170000 cfs

Sl. No.	Year	Month	Date of peak	Flood peak (cfs)	Flood month mean monthly flow at		Range excess over TRY	Actual excess value at MAH	Flood type
					Mortakka	MAH			
1	1959	Sept	15	971385	225141	235162	0-30000	65162	1
2	1961	Sept	17	1191020	362255	370800	30001-85000	200800	2
3	1970	Sept	6	1366240	270112	279192	85001-165000	109192	3
4	1975	Sept	13	1029350	172187	175827	> 165000	5827	4

3-hourly mean flows is given in Table 5.3.5. Other data like elevation-area-capacity, monthly evaporation rate, monthly release policy, and maximum and minimum permissible storage at the end of each month for each reservoir, are given in Tables 5.3.6 to 5.3.19.

The net inflow to any reservoir is taken as the inflow due to independent catchment area - (u/s water requirements for major projects, medium, minor and pumping schemes) + Regenerated flows + Release from the u/s reservoir.

5.4. Simulation Procedure

A simulation program developed by the HEC (1966) namely 'Reservoir yield' is used in the present study after making suitable modification in the program. The design variables obtained from the steepest ascent method are used as input data. Other data needed for simulation are described in Section 5.3. The system performance is tested using historical streamflow data of 28 years and generated streamflow data of 50 years for each simulation run.

The water requirements and releases are taken from the NWDT award (see Appendix). A study is also carried out using modified water requirements and releases modified according to the classification of the basin as very wet, wet, average and dry year. The 75% dependable flow at Sardar Sarovar denoted by, say, W is fixed as 27 MAF on the basis of 79 years of annual flow series available at Sardar Sarovar. If the flow at Sardar Sarovar in any year is more than 1.5 W, the year is termed as very wet, and the water requirements and

TABLE 5.3.5. FLOOD RELEASE POLICY FOR FLOOD MONTH

Total 3-hourly mean flow = Flood ordinate + Release from upstream reservoir (cfs)	Flood release (cfs)
0 - 50000	15000
50001 - 75000	20000
75001 - 100000	25000
100001 - 200000	30000
200001 - 300000	35000
300001 - 400000	40000
400001 - 500000	45000
500001 - 600000	50000
600001 - 750000	60000
> 750001	70000

TABLE 5.3.6. ELEVATION-AREA-CAPACITY DATA

BARGI

Sl. No.	Elevation in feet	Area in acres	Storage capacity in MAF
1	1300	6225	0.210
2	1320	14993	0.548
3	1324	18278	0.600
4	1340	25565	1.100
5	1360	41250	1.800
6	1380	60000	2.749
7	1387	66750	3.180
8	1390	69750	3.406
9	1400	83500	4.055
10	1410	97500	4.750
11	1420	115000	5.650
12	1426	130200	6.250
13	1430	143500	6.600
14	1435	160000	7.500

TABLE 5.3.7. ELEVATION-AREA-CAPACITY DATA

NARMADASAGAR

Sl. No.	Elevation in feet	Area in acres	Storage capacity in MAF
1	690	000	0.000
2	700	2700	0.120
3	710	3900	0.160
4	720	4240	0.193
5	730	5000	0.210
6	740	6960	0.304
7	750	11000	0.385
8	760	18040	0.505
9	770	27000	0.770
10	780	38040	1.100
11	790	52000	1.500
12	798	63800	2.000
13	800	66040	2.150
14	810	82000	2.870
15	820	99800	3.760
16	830	121000	4.700
17	840	147300	6.210
18	850	180000	7.800
19	860	224840	9.900
20	864	238000	10.800
21	870	266000	12.500
22	880	308000	16.000
23	890	360000	20.000
24	900	430000	25.500

TABLE 5.3.8. ELEVATION-AREA-CAPACITY DATA

OMKARESHWAR

Sl. No.	Elevation in feet	Area in acres	Storage capacity in MAF
1	510	0	0.0000
2	520	75	0.0025
3	530	300	0.0075
4	540	650	0.0130
5	550	1126	0.0225
6	560	1700	0.0410
7	570	2400	0.0630
8	580	3300	0.0910
9	590	4540	0.1280
10	600	6100	0.1800
11	610	8050	0.2470
12	620	11100	0.3470
13	630	15100	0.4800
14	635	17950	0.5600
15	640	21100	0.6560
16	650	28360	0.9000
17	660	34976	1.2160
18	665	41500	1.4375
19	670	45952	1.6190
20	675	55000	1.8750
21	680	75000	2.5000

TABLE 5.3.9. ELEVATION-AREA-CAPACITY DATA

MAHESHWAR

Sl. No.	Elevation in feet	Area in acres	Storage capacity in MAF
1	456	0	0.00000
2	460	500	0.00067
3	470	1300	0.00935
4	480	2400	0.02757
5	490	3700	0.05741
6	500	5400	0.10307
7	510	7000	0.16490
8	520	9350	0.24537
9	530	11000	0.34800
10	532	11800	0.37500
11	534	12000	0.39800
12	540	13800	0.47175
13	545	16000	0.55000
14	550	18150	0.63100
15	555	21000	0.75000
16	560	24000	0.85000
17	565	28000	0.95000
18	570	34000	1.15000
19	575	38000	1.30000
20	580	44000	1.50000
21	585	52000	1.70000
22	590	64000	2.00000
23	595	80000	2.30000

TABLE 5.3.10. ELEVATION-AREA-CAPACITY DATA

SARDAR SAROVAR

Sl. No.	Elevation in feet	Area in acres	Storage capacity in MAF
1	100	1208	0.000
2	120	1998	0.080
3	140	2761	0.100
4	160	4155	0.150
5	180	5162	0.240
6	200	6468	0.360
7	220	8260	0.500
8	240	9968	0.700
9	260	12340	0.920
10	280	14340	1.120
11	300	17688	1.540
12	320	21188	1.940
13	340	22852	2.380
14	360	27224	2.880
15	363	28200	2.970
16	380	33372	3.480
17	400	41532	4.280
18	420	55148	5.190
19	440	70340	6.440
20	455	91340	7.700
21	460	99969	8.140
22	465	107500	9.000
23	470	117500	9.500
24	475	125000	10.150
25	480	135000	11.000
26	492	150000	13.230

TABLE 5.3.11. MONTHLY EVAPORATION RATE

BARGI			NARMADASAGAR		
Sl. No.	Month	Evaporation rate in inches	Sl. No.	Month	Evaporation rate in inches
1	July	2.5	1	July	5.44
2	Aug	2.3	2	Aug	5.48
3	Sept	3.1	3	Sept	5.10
4	Oct	4.0	4	Oct	5.32
5	Nov	3.1	5	Nov	4.20
6	Dec	2.4	6	Dec	3.60
7	Jan	2.8	7	Jan	4.30
8	Feb	3.7	8	Feb	5.10
9	March	7.3	9	March	8.76
10	April	11.6	10	April	13.20
11	May	15.6	11	May	15.20
12	June	7.7	12	June	10.00

TABLE 5.3.12. MONTHLY EVAPORATION RATE

OMKARESHWAR			MAHESHWAR		
Sl. No.	Month	Evaporation rate in inches	Sl. No.	Month	Evaporation rate in inches
1	July	5.1	1	July	5.1
2	Aug	4.8	2	Aug	4.8
3	Sept	5.0	3	Sept	5.0
4	Oct	5.2	4	Oct	5.2
5	Nov	3.8	5	Nov	3.8
6	Dec	3.3	6	Dec	3.3
7	Jan	3.8	7	Jan	3.8
8	Feb	4.5	8	Feb	4.5
9	March	6.6	9	March	6.6
10	April	8.1	10	April	8.1
11	May	10.6	11	May	10.6
12	June	8.1	12	June	8.1

TABLE 5.3.13. MONTHLY EVAPORATION RATE

SARDAR SAROVAR

Sl. No.	Month	Evaporation rate in inches
1	July	3.30
2	Aug	3.00
3	Sept	4.44
4	Oct	6.46
5	Nov	5.87
6	Dec	4.73
7	Jan	5.50
8	Feb	6.39
9	March	9.80
10	April	12.00
11	May	12.90
12	June	8.00

TABLE 5.3.14. MONTHLY RELEASE POLICY

BARGI			NARMADASAGAR		
Sl. No.	Month	Release in cfs	Sl. No.	Month	Release in cfs
1	July	260	1	July	13224
2	Aug	3306	2	Aug	24795
3	Sept	3306	3	Sept	56203
4	Oct	104	4	Oct	3306
5	Nov	104	5	Nov	3306
6	Dec	52	6	Dec	3306
7	Jan	52	7	Jan	3306
8	Feb	52	8	Feb	3306
9	March	52	9	March	1653
10	April	52	10	April	1653
11	May	52	11	May	1653
12	June	52	12	June	1653
	Total	7444 (0.45 MAF)		Total	117364 (7.10 MAF)

TABLE 5.3.15. MONTHLY RELEASE POLICY

OMKARESHWAR			MAHESHWAR		
Sl. No.	Month	Release in cfs	Sl. No.	Month	Release in cfs
1	July	13224	1	July	11569
2	Aug	24795	2	Aug	24795
3	Sept	56202	3	Sept	59508
4	Oct	4133	4	Oct	4133
5	Nov	4133	5	Nov	4133
6	Dec	4133	6	Dec	4133
7	Jan	4133	7	Jan	4133
8	Feb	4133	8	Feb	4133
9	March	2479	9	March	2479
10	April	2479	10	April	2479
11	May	2479	11	May	2479
12	June	2479	12	June	2479
	Total	124803 (7.55 MAF)		Total	126453 (7.65 MAF)

TABLE 5.3.16. MONTHLY RELEASE POLICY

SARDAR SAROVAR

Sl. No.	Month	Release in cfs
1	July	16
2	Aug	99
3	Sept	16
4	Oct	16
5	Nov	16
6	Dec	16
7	Jan	16
8	Feb	16
9	March	16
10	April	16
11	May	16
12	June	16
	Total	275 (0.0167 MAF)

TABLE 5.3.17. MINIMUM AND MAXIMUM PERMISSIBLE STORAGE AT THE END OF EACH MONTH

BARGI				NARMADASAGAR			
Sl. No.	Month	Minimum MAF	Maximum MAF	Sl. No.	Month	Minimum MAF	Maximum MAF
1	July	0.6000	1.8750	1	July	2.0000	4.5000
2	Aug		4.3750	2	Aug		10.5000
3	Sept		6.2500	3	Sept		15.0000
4	Oct		5.6250	4	Oct		13.5000
5	Nov		4.6875	5	Nov		11.2500
6	Dec		4.0625	6	Dec		9.7500
7	Jan		3.7500	7	Jan		9.0000
8	Feb		3.4375	8	Feb		8.2500
9	March		3.1250	9	March		7.5000
10	April		2.8125	10	April		6.7500
11	May		2.5000	11	May		6.0000
12	June		2.1875	12	June		5.2500

TABLE 5.3.18. MINIMUM AND MAXIMUM PERMISSIBLE STORAGE AT THE END OF EACH MONTH

<table>
<tr><th colspan="4">OMKARESHWAR</th><th colspan="4">MAHESHWAR</th></tr>
<tr><th>Sl. No.</th><th>Month</th><th>Minimum MAF</th><th>Maximum MAF</th><th>Sl. No.</th><th>Month</th><th>Minimum MAF</th><th>Maximum MAF</th></tr>
<tr><td>1</td><td>July</td><td rowspan="12">0.5600</td><td>0.6400</td><td>1</td><td>July</td><td rowspan="12">0.3750</td><td>0.3750</td></tr>
<tr><td>2</td><td>Aug</td><td>1.1200</td><td>2</td><td>Aug</td><td>0.3800</td></tr>
<tr><td>3</td><td>Sept</td><td>1.6000</td><td>3</td><td>Sept</td><td>0.4000</td></tr>
<tr><td>4</td><td>Oct</td><td>1.4400</td><td>4</td><td>Oct</td><td>0.3950</td></tr>
<tr><td>5</td><td>Nov</td><td>1.2800</td><td>5</td><td>Nov</td><td>0.3900</td></tr>
<tr><td>6</td><td>Dec</td><td>1.2000</td><td>6</td><td>Dec</td><td>0.3850</td></tr>
<tr><td>7</td><td>Jan</td><td>1.0400</td><td>7</td><td>Jan</td><td>0.3800</td></tr>
<tr><td>8</td><td>Feb</td><td>0.9600</td><td>8</td><td>Feb</td><td>0.3750</td></tr>
<tr><td>9</td><td>March</td><td>0.8800</td><td>9</td><td>March</td><td>0.3750</td></tr>
<tr><td>10</td><td>April</td><td>0.8000</td><td>10</td><td>April</td><td>0.3750</td></tr>
<tr><td>11</td><td>May</td><td>0.7200</td><td>11</td><td>May</td><td>0.3750</td></tr>
<tr><td>12</td><td>June</td><td>0.6400</td><td>12</td><td>June</td><td>0.3750</td></tr>
</table>

TABLE 5.3.19. MINIMUM AND MAXIMUM STORAGE PERMISSIBLE STORAGE AT THE END OF EACH MONTH

SARDAR SAROVAR

Sl. No.	Month	Minimum MAF	Maximum MAF
1	July	2.9700	3.1000
2	Aug		5.4250
3	Sept		7.7500
4	Oct		7.3625
5	Nov		7.1688
6	Dec		6.9750
7	Jan		6.7813
8	Feb		6.5875
9	March		6.3937
10	April		6.2000
11	May		6.0000
12	June		5.7800

releases are increased by 5%. If the flow at Sardar Sarovar in any year is greater than 1.1 W, but less than 1.5 W, the year is defined as wet. and water requirements and releases are increased by 2.5%. If the flow at Sardar Sarovar in any year is less than 0.9 W, the year is classified as dry and water requirements and releases are decreased by 7.5%. If the flow at Sardar Sarovar in any year is between 0.9 W and 1.1 W, the year is termed as average year. and water requirements and releases are taken same as normal demands and releases respectively.

It is necessary to use some type of loss functions to evaluate the economic consequences of failure to meet target outputs. This failure is due to uncertainties caused by stochastic nature of both supply and demand. The shortage index as defined by Beard (1970) is used in the simulation program and is discussed in the next section. In addition to Beard's shortage index concept, a second method based on classification of shortages into different types, is also used. The different types are shown in a tabular form below.

Annual irrigation shortages

Particulars	Shortage ratio
Type 1	0.00 - 0.05
Type 2	0.06 - 0.10
Type 3	0.11 - 0.15
Type 4	0.16 - 0.20
Type 5	0.21 - 0.25
Type 6	0.26 - 0.30
Type 7	0.31 - 0.35
Type 8	0.36 - 0.40
Type 9	0.41 - 0.45
Type 10	0.46 - 0.50
Type 11	$>$ 0.51

Monthly power shortages for each season

Particular	Shortage ratio
Type 1	0.00 - 0.50
Type 2	0.06 - 0.10
Type 3	0.11 - 0.15
Type 4	0.16 - 0.20
Type 5	0.21 - 0.25
Type 6	> 0.26

Shortage = Required quantity - Actual quantity supplied

$$\text{Shortage ratio} = \frac{\text{Shortage}}{\text{Required quantity}}$$

5.5. Concept of Shortage Index

Fiering (1969) gave the following expression for loss function;

$$L = \sum_{t=1}^{T} L_t \tag{5.4}$$

where,

$$L_t = \left(\sum_{i=1}^{p} b_{i,t} \, SH_{i,t}^{K_1} \right) N_t^{\alpha_1} \tag{5.5}$$

in which,

L = total loss in T periods;

L_t = loss in period t;

p = number of subperiod i in period t;

$SH_{i,t}$ = shortage in subperiod i (positive or otherwise zero) in period t;

N_t = number of consecutive shortages in period t;

$b_{i,t}$ = coefficient (derived from the relationship between economic loss and water shortage);

K_1, α_1 = coefficients.

Beard (1970) defined shortage index as the sum of the square of annual shortage ratios over a 100-year period. This shortage ratio is the difference between quantity of water required and supplied, divided by the quantity required. He gives the following expression;

$$SHI = \sum_{t=1}^{T} (SH_t^2) \times \frac{100}{T} \tag{5.6}$$

where,

$$SH_t = \frac{Y'_t - Y_t}{Y'_t} \tag{5.7}$$

in which,

Y'_t = quantity of water required in period t;

Y_t = quantity of water supplied in period t;

T = number of years considered.

One can get the same expression as (5.6) by substituting $\alpha_1 = 0$; $p = 1$; $K_1 = 2$ and assuming b as constant in equation (5.5). There are certain advantages claimed by shortage index concept in the economic evaluation of water resource system as listed below;

(a) Shortage index is a single representative value for all shortages occurring during the economic life of a project for a given sequence of supply and demand.

(b) The magnitude and frequency of shortages are predicted. If shortage index is 0.25, it may mean 25 annual shortages

of 10% each or 10 annual shortages of about 16% each, or 100 annual shortages of 5% each, over a period of 100 years. Losses that occur near the beginning of the project life have severe effect than those occur near the end of the economic life of project. Hence average economic effect is considered for each project.

5.5.1. Evaluation of constant b

One can easily find the loss function if the value of $b_{i,t}$ is known in equation (5.5). Assuming an average square shortage ratio, and b as a constant, one can write the loss as;

$$L = b(\overline{SH^2}) \tag{5.8}$$

in which,

$(\overline{SH^2})$ = average of squared shortage ratio, i.e., $\sum_{t=1}^{T} SH_t^2/T$

$b(\overline{SH^2})$ = annual average losses as a ratio to gross annual benefits.

We know, shortage index SHI $= \sum_{t=1}^{T} (SH_t^2) \times \frac{100}{T}$

$$\therefore \quad SHI = \sum_{t=1}^{T} (SH_t^2/T) \times 100$$

$$\therefore \quad SHI = 100 \times \overline{SH^2} \tag{5.9}$$

$$\therefore \quad L = \frac{b \times SHI}{100} \tag{5.10}$$

For the whole system, the loss function for irrigation is

$$L_{IRR} = \sum_{i=1}^{5} b_{1,i} \, SHI_{1,i} \, IR_i \, IRR_i \tag{5.11}$$

in which,

L_{IRR} = annual loss for irrigation in whole system in 10^7 rupees;

IR = annual benefits in 10^7 rupees/MAF;

IRR = actual irrigation target met in MAF;

SHI_1 = shortage index for irrigation.

The same loss function is assumed for energy.

$$L_{ENG} = \sum_{i=1}^{5} b_{2,i} \, SHI_{2,i} \, PE_i \, EACT_i \tag{5.12}$$

in which,

L_{ENG} = annual loss for energy in whole system in 10^7 rupees;

PE = energy price/kwhr;

EACT = actual energy produced in kwhr;

SHI_2 = shortage index for energy.

Now the problem is to determine the value of b_1 and b_2 for each project. If the actual data of annual losses and annual shortages were available, one can evaluate the values of b_1 and b_2 by fitting a quadratic function of the type $\bar{y} = b_1(\overline{SH_1^2})$ for irrigation and $\bar{y} = b_2(\overline{SH_2^2})$ for power.

Irrigation is given first priority in the present study, hence irrigation shortages may be more serious than power shortages. As no data are available to construct quadratic function, the value of b_1 for irrigation is taken as 10.0 for

each project. The power shortages are considered to be less effective, the value of b_2 is assumed as 8.0 (Martinez, 1971).

5.6. Simulation Runs

The following simulation runs were conducted;

(1) Monthly simulation runs are conducted by considering water requirements and releases according to (i) tribunal award, (ii) classification of year as very wet, wet, average and dry.

(2) In order to know 3-hourly maximum spill from the terminal reservoir, the flood subroutine is activated and 3-hourly flood routing is carried out for the flood month having monthly meanflow greater than the specified trigger value at reservoir sites.

For the first study, four simulation runs for each case using historical flow and synthetic flow are carried out while for latter study two simulation runs are carried out. The results of the simulation runs are tabulated in Tables 6.4.1 to 6.4.60.

CHAPTER 6

RESULTS AND DISCUSSIONS

6.1. Streamflow Generation

Twenty eight years of historical streamflow record at the three gauging sites are available. Using this, two hundred and fifty years of synthetic flows are generated at each reservoir site using HEC-4 program. This program occupies about 50 K memory on DEC-1090 computer system. It requires about 80 seconds to generate two hundred and fifty years of data. Tables 6.1.1 to 6.1.5 show monthly and annual means and standard deviations of flow at all the sites. It may be seen that the mean and standard deviation of generated flows are close to historical streamflows at all stations.

6.2. LPD Model

The following configurations are studied with LPD model (Table 6.2.1). The model is run for different cases such as linear and nonlinear objective function, and different flow conditions like 1.25 times average flow, average flow, and 0.9 times average flow. Another configuration in which release is allowed to pass through turbine for power generation and then to irrigate the land is also studied. Fourteen alternatives out of the possible twenty four are studied. Each run takes about two minutes CPU time. The results are tabulated in Tables 6.2.2 to 6.2.5. Based on these results, limits on various design variables are selected as shown in Table 6.2.6

TABLE 6.1.1. COMPARISON OF STATISTICAL PARAMETERS AND OTHER INFORMATION FOR HISTORICAL AND GENERATED STREAMFLOWS

Station No. and name of station	Month		Flow (sum) cfs	Flow (max) cfs	Flow (min) cfs	Flow (mean) cfs	Standard deviation cfs
101 Bargi	July	H*	692713	73431	1408	24740	16496
		G*	6254277	61575	0	25017	14617
	Aug	H	1307568	83722	8047	46699	16733
		G	11617173	78317	4227	46469	17654
	Sept	H	772670	69946	3310	27595	15360
		G	6752786	84036	2978	27011	14724
	Oct	H	196507	20211	805	7018	5449
		G	1369017	40374	572	6676	5392
	Nov	H	54675	8715	352	1953	1648
		G	440976	5990	227	1764	1114
	Dec	H	27457	4302	294	981	774
		G	242725	8969	231	971	816
	Jan	H	18987	2723	201	678	490
		G	180467	7945	142	722	680
	Feb	H	11956	1113	137	427	243
		G	113807	2840	75	455	304
	March	H	8357	805	62	298	208
		G	81078	3501	20	324	302
	April	H	4991	736	16	178	163
		G	48405	1975	13	194	211
	May	H	1621	201	15	58	46
		G	13667	269	6	55	48
	June	H	48786	15991	16	1742	3173
		G	339758	15960	0	1369	1929
Annual Statistics		H	3146288	231120	35895	112367	43061
		G	27754136	232076	26178	111017	36708

*H stands for historical and G for generated flows.

TABLE 6.1.2. COMPARISON OF STATISTICAL PARAMETERS AND OTHER INFORMATION FOR HISTORICAL AND GENERATED STREAMFLOWS

Station No. and name of station	Month		Flow (sum) cfs	Flow (max) cfs	Flow (min) cfs	Flow (mean) cfs	Standard deviation cfs
102 Narmada Sagar	July	H*	1356572	188591	11314	48449	37082
		G*	10057156	145813	5770	40229	24100
	Aug	H	2945551	195060	19119	105198	45035
		G	23946667	195623	13194	95787	40338
	Sept	H	2808165	260660	19770	100292	63115
		G	24406818	661820	17059	97627	77641
	Oct	H	655923	70928	3704	23426	17103
		G	6227084	145280	3049	24908	20392
	Nov	H	219812	19425	2061	7850	4750
		G	2106158	35090	1625	8425	5707
	Dec	H	125550	8234	1536	4484	1793
		G	1125604	12418	1232	4502	1882
	Jan	H	90414	5877	1242	3229	1231
		G	811943	8330	1084	3248	1307
	Feb	H	70948	4299	969	2534	807
		G	617566	5299	808	2470	845
	March	H	52243	3223	387	1866	657
		G	472963	3271	386	1892	664
	April	H	40622	3330	599	1451	631
		G	367468	5280	516	1470	646
	May	H	27873	1700	466	995	362
		G	252009	2839	362	1008	363
	June	H	109749	18199	221	3920	4591
		G	1014309	32029	88	4057	5092
Annual Statistics		H	8503422	641561	98195	303694	120933
		G	71405745	912508	97889	285623	112076

*H stands for historical and G for generated flows.

TABLE 6.1.3. COMPARISON OF STATISTICAL PARAMETERS AND OTHER INFORMATION FOR HISTORICAL AND GENERATED STREAMFLOWS

Station No. and name of station	Month		Flow (sum) cfs	Flow (max) cfs	Flow (min) cfs	Flow (mean) cfs	Standard deviation cfs
	July	H*	94924	13447	763	3390	2638
		G*	698066	9873	371	2792	1681
	Aug	H	206823	13803	1344	7387	3205
		G	1677367	13963	922	6709	2856
	Sept	H	198911	18470	1408	7104	4486
		G	1729820	47294	1186	6919	5534
	Oct	H	46400	5046	263	1657	1213
		G	441323	10314	216	1765	1448
	Nov	H	15591	1380	146	557	339
		G	149673	2499	115	599	406
103 Omkar-eshwar	Dec	H	8916	587	109	318	127
		G	79924	879	88	320	134
	Jan	H	6426	417	88	230	88
		G	57692	591	78	231	93
	Feb	H	5048	306	69	180	58
		G	43938	381	58	176	60
	March	H	3722	230	26	133	47
		G	34508	250	20	138	54
	April	H	2899	238	43	104	45
		G	34206	1318	14	137	141
	May	H	1997	122	33	71	26
		G	21099	482	13	84	58
	June	H	7714	1294	13	276	322
		G	62665	1662	07	251	276
Annual Statistics		H	599371	45536	6933	21406	8583
		G	5030281	65149	6860	20121	7993

*H stands for historical and G for generated flows.

TABLE 6.1.4. COMPARISON OF STATISTICAL PARAMETERS AND OTHER INFORMATION FOR HISTORICAL AND GENERATED STREAMFLOWS

Station No. and name of station	Month		Flow (sum) cfs	Flow (max) cfs	Flow (min) cfs	Flow (mean) cfs	Standa. deviat. cfs
104 Maheshwar	July	H*	76114	13673	0	2718	2541
		G*	550816	3752	0	2203	1207
	Aug	H	195818	14933	2031	6994	3443
		G	1689339	20970	1296	6757	3553
	Sept	H	243877	21724	1751	8710	6295
		G	2165054	55836	857	8660	7877
	Oct	H	57012	9173	0	2036	2051
		G	517532	7590	0	2070	1706
	Nov	H	16357	1938	0	584	421
		G	130629	1048	1	523	320
	Dec	H	8462	969	0	302	191
		G	70468	481	0	282	153
	Jan	H	5875	805	0	210	149
		G	52844	336	0	211	104
	Feb	H	4684	663	0	167	120
		G	39884	251	0	160	76
	March	H	3106	413	0	111	76
		G	28022	183	0	112	58
	April	H	2187	280	0	78	56
		G	19742	158	0	79	48
	May	H	1532	219	0	55	41
		G	11091	77	0	44	21
	June	H	13451	4194	0	480	818
		G	133857	6067	0	535	867
Annual Statistics		H	628475	48399	7009	22446	10501
		G	5409278	73638	4993	21637	9859

*H stands for historical and G for generated flows.

TABLE 6.1.5. COMPARISON OF STATISTICAL PARAMETERS AND OTHER INFORMATION FOR HISTORICAL AND GENERATED STREAMFLOWS

Station No. and name of station	Month		Flow (sum) cfs	Flow (max) cfs	Flow (min) cfs	Flow (mean) cfs	Standard deviation cfs
105 Sardar Sarovar	July	H*	2297025	281835	25340	82037	55346
		G*	19574078	344957	17484	78296	41791
	Aug	H	5110391	335597	40642	182514	69689
		G	44154058	351609	26872	176616	69621
	Sept	H	4984461	451335	33270	178016	114594
		G	43302035	999898	31137	173208	132985
	Oct	H	1177105	151068	6471	42039	34411
		G	11628423	381146	6378	46514	44577
	Nov	H	355097	28624	2714	12682	6945
		G	3329294	53689	2157	13317	8596
	Dec	H	189706	14283	1895	6775	2654
		G	1753853	22746	1967	7015	3091
	Jan	H	133506	12571	1557	4768	2221
		G	1301783	18086	1614	5207	2408
	Feb	H	102368	9501	1288	3656	1605
		G	984602	12665	1105	3938	1742
	March	H	71493	6117	881	2553	1132
		G	708915	8647	582	2836	1258
	April	H	51690	4222	563	1846	872
		G	518609	8730	673	2074	1026
	May	H	33879	3201	397	1210	596
		G	329730	7704	429	1319	663
	June	H	271858	58114	487	9709	13344
		G	2509253	98978	652	10037	12630
Annual Statistics		H	14778579	1036638	164069	527806	210408
		G	130094630	1431669	182185	520379	194600

*H stands for historical and G for generated flows.

TABLE 6.2.1. TYPES OF CONFIGURATIONS

Configuration number	Name of project	Purposes		
		Irrigation	Energy	
			RBPH	CHPH
1	Bargi	Yes	No	No
	Narmadasagar	Yes	Yes	No
	Omkareshwar	Yes	Yes	No
	Maheshwar	No	Yes	No
	Sardar Sarovar	Yes	No	Yes
2	Bargi	Yes	Yes	No
	Narmadasagar	Yes	Yes	No
	Omkareshwar	Yes	Yes	No
	Maheshwar	No	Yes	No
	Sardar Sarovar	Yes	No	Yes
3	Bargi	Yes	No	Yes
	Narmadasagar	Yes	Yes	No
	Omkareshwar	Yes	Yes	No
	Maheshwar	No	Yes	No
	Sardar Sarovar	Yes	No	Yes
4*	Bargi	Yes	Yes	
	Narmadasagar	Yes	Yes	
	Omkareshwar	Yes	Yes	
	Maheshwar	Yes	Yes	
	Sardar Sarovar	Yes	Yes	

*In configuration 4 release is allowed to pass through turbines for power generation and then to irrigate the land.

RBPH - River bed power house
CHPH - Canal head power house.

TABLE 6.2.2. RESULTS OF LPD MODEL FOR CONFIGURATION 1

Variable	Objective function					
	Linear			Nonlinear		
	1.25 times average flow	Average flow	0.9 times average flow	1.25 times average flow	Average flow	0.9 times average flow
I1	8.930	7.146	6.431	4.500	4.000	3.500
Y1	6.070	4.980	4.540	2.880	2.710	2.430
E1	0.000	0.000	0.000	0.000	0.000	0.000
I2	12.720	6.660	7.120	11.000	10.350	9.250
Y2	13.260	11.600	10.450	14.720	13.250	12.260
E2+	1601.000	1802.000	1456.000	2000.000	1526.000	1400.000
I3	5.260	6.270	5.080	4.750	4.150	3.750
Y3	1.020	0.880	0.830	0.560	1.000	0.940
E3+	787.000	693.000	584.000	1000.000	800.000	750.000
Y4	0.375	0.375	0.375	0.375	0.375	0.375
E4+	559.000	550.000	464.000	600.000	600.000	550.000
I5	13.800	10.300	9.550	10.400	9.500	8.500
Y5	6.850	7.750	5.580	5.640	6.080	4.950
E5*	1253.000	1153.000	996.000	1200.000	1150.000	1000.000
Net benefits in 10^7 Rupees	188.240	171.150	156.370	125.680	113.750	107.480

I, Y are in MAF and E is in million kwhr.

* CHPH considered

\+ RBPH considered.

TABLE 6.2.3. RESULTS OF LPD MODEL FOR CONFIGURATION 2

Variable	Objective function
	Nonlinear
	Average flow
I1	3.950
Y1	5.000
E1+	300.000
I2	10.400
Y2	11.060
E2+	1674.000
I3	4.150
Y3	0.650
E3+	800.000
Y4	0.375
E4+	600.000
I5	9.500
Y5	6.350
E5*	1150.000
Net benefits in 10^7 Rupees	149.660

I, Y are in MAF and E is in million kwhr.

+ RBPH considered

* CHPH considered

Note: In this configuration only average flow case is included.

TABLE 6.2.4. RESULTS OF LPD MODEL FOR CONFIGURATION 3

Variable	Objective function					
	Linear			Nonlinear		
	1.25 times average flow	Average flow	0.9 times average flow	1.25 times average flow	Average flow	0.9 times average flow
I1	8.930	7.146	6.430	-	3.800	-
Y1	6.070	4.980	4.540	-	5.220	-
E1*	173.000	139.000	125.000	-	150.000	-
I2	11.700	5.470	4.530	-	10.000	-
Y2	13.430	11.800	10.880	-	12.500	-
E2+	1752.000	1979.000	1839.000	-	1609.000	-
I3	5.240	6.140	7.560	-	4.000	-
Y3	1.010	0.880	1.240	-	0.760	-
E3+	874.000	805.000	564.000	-	758.000	-
Y4	0.375	0.375	0.375	-	0.375	-
E4+	617.000	624.000	468.000	-	575.000	-
I5	13.270	9.620	9.500	-	9.600	-
Y5	6.700	5.880	5.610	-	6.150	-
E5*	1383.000	1253.000	1004.000	-	1175.000	-
Net benefits in 10^7 Rupees	213.430	181.130	162.130	-	116.230	-

I, Y are in MAF and E is in million kwhr.

* CHPH considered

\+ RBPH considered

Note: Only average flow case is studied in case of nonlinear objective function.

TABLE 6.2.5. RESULTS OF LPD MODEL FOR CONFIGURATION 4

Variable	Objective function		
	Linear		
	1.25 times average flow	Average flow	0.9 times average flow
I1	8.750	7.150	6.430
Y1	6.125	4.980	4.540
E1	193.000	139.000	125.000
I2	6.740	12.340	12.300
Y2	15.340	12.200	10.690
E2	3514.000	2692.000	2328.000
I3	10.390	3.030	1.530
Y3	1.040	1.870	1.650
E3	1793.000	840.000	656.000
Y4	1.490	0.550	0.430
E4	727.000	450.000	391.000
I5	13.270	11.540	10.390
Y5	7.750	7.750	5.860
E5	1383.000	778.000	700.000
Net benefits in 10^7 Rupees	268.220	207.400	181.940

I, Y are in MAF and E is in million kwhr.

Note: In this configuration only linear objective function is considered.

TABLE 6.2.6. LIMITS ASSUMED FOR EACH VARIABLE

Variable	Limits assumed
I1	2 - 5
Y1	3 - 7
E1	50 - 150
I2	5 - 13
Y2	10 - 16
E2	600 - 1600
I3	2 - 5
Y3	0.5 - 2.0
E3	600 - 1000
Y4	0.3 - 0.7
E4	200 - 600
I5	7 - 10
Y5	7 - 8
E5	600 - 1100

I, Y are in MAF and E is in million kwhr.

for use in steepest ascent analysis. It is found that for each configuration the benefits are larger in the case of linear objective function than in the case of nonlinear objective function.

6.3. Steepest Ascent Method

The range for each variable is fixed on the basis of information obtained from LPD results. A set of variables is assumed arbitrarily within this range as a starting base. The objective function developed for LPD model is used to represent response surface. The net benefits for nine samples are obtained and tabulated in Tables 6.3.1 to 6.3.9 as already mentioned in the last chapter. A set of variable which produces maximum net benefit is selected as input data for simulation study. This set is shown in Table 6.3.10.

6.4. Simulation

The design variables obtained from steepest ascent method of sampling are used in simulation analysis. Simulation can be conducted by adopting various operating policies. An operating policy is a statement which stipulates the amount of water to be kept in storage at the end of a period, say a month, and the amount of water to be released during the month. This decision depends upon the configuration of reservoirs, and the purpose for which the system has been designed. The purpose may be conflicting or complementary. For instance, flood control requires that the reservoir should be kept as empty as possible to hold expected flood, whereas water should be held

TABLE 6.3.1. RESULTS OF STEEPEST ASCENT METHOD FOR SAMPLE 1

Variable	Assumed limits of variable	Range	Starting base value	Final value
1	2	3	4	5
I1	2 - 5	3.0	2.0	3.600
Y1	3 - 7	4.0	3.0	1.500
E1	50 - 150	100.0	50.0	27.000
I2	5 - 13	8.0	5.0	8.600
Y2	10 - 16	6.0	10.0	9.430
E2	600 - 1600	1000.0	600.0	2000.000
I3	2 - 5	3.0	2.0	2.800
Y3	0.5 - 2.0	1.5	0.5	0.230
E3	600 - 1000	400.0	600.0	761.000
Y4	0.3 - 0.7	0.4	0.4	0.398
E4	200 - 600	400.0	200.0	403.000
I5	7 - 10	3.0	7.0	7.840
Y5	7 - 8	1.0	7.0	6.960
E5	600 - 1100	500.0	600.0	882.000

Net benefit = Rs. 113.93 x 10^7

I, Y are in MAF and E is in million kwhr.

TABLE 6.3.2. RESULTS OF STEEPEST ASCENT METHOD FOR SAMPLE 2

Variable	Assumed limits of variable	Range	Starting base value	Final value
1	2	3	4	5
I1	2 - 5	3.0	2.15	3.730
Y1	3 - 7	4.0	4.00	2.680
E1	50 - 150	100.0	60.00	37.200
I2	5 - 13	8.0	6.00	8.890
Y2	10 - 16	6.0	11.00	10.510
E2	600 - 1600	1000.0	625.00	2025.000
I3	2 - 5	3.0	2.25	3.040
Y3	0.5 - 2.0	1.5	0.75	0.530
E3	600 - 1000	400.0	650.00	807.000
Y4	0.3 - 0.7	0.4	0.41	0.409
E4	200 - 600	400.0	250.00	445.000
I5	7 - 10	3.0	7.50	8.220
Y5	7 - 8	1.0	7.25	7.210
E5	600 - 1100	500.0	650.00	931.000

Net benefit = Rs.115.05 x 10^7

I, Y are in MAF and E is in million kwhr.

TABLE 6.3.3. RESULTS OF STEEPEST ASCENT METHOD FOR SAMPLE 3

Variable	Assumed limits of variable	Range	Starting base value	Final value
1	2	3	4	5
I1	2 - 5	3.0	2.30	3.800
Y1	3 - 7	4.0	5.00	3.860
E1	50 - 150	100.0	70.00	47.400
I2	5 - 13	8.0	7.00	9.190
Y2	10 - 16	6.0	12.00	11.590
E2	600 - 1600	1000.0	650.00	2050.000
I3	2 - 5	3.0	2.50	3.280
Y3	0.5 - 2.0	1.5	1.00	0.840
E3	600 - 1000	400.0	700.00	853.000
Y4	0.3 - 0.7	0.4	0.42	0.418
E4	200 - 600	400.0	300.00	487.000
I5	7 - 10	3.0	8 00	8.600
Y5	7 - 8	1.0	7.50	7.460
E5	600 - 1100	500.0	700.00	980.000

Net benefit = Rs.116.32 x 10^7

I, Y are in MAF and E is in million kwhr.

TABLE 6.3.4. RESULTS OF STEEPEST ASCENT METHOD FOR SAMPLE 4

Variable	Assumed limits of variable	Range	Starting base value	Final value
1	2	3	4	5
I1	2 - 5	3.0	2.45	3.910
Y1	3 - 7	4.0	6.00	5.040
E1	50 - 150	100.0	80.00	57.610
I2	5 - 13	8.0	8.00	9.460
Y2	10 - 16	6.0	13.00	12.660
E2	600 - 1600	1000.0	675.00	2075.000
I3	2 - 5	3.0	2.75	3.530
Y3	0.5 - 2.0	1.5	1.25	1.140
E3	600 - 1000	400.0	725.00	877.000
Y4	0.3 - 0.7	0.4	0.43	0.428
E4	200 - 600	400.0	325.00	509.000
I5	7 - 10	3.0	8.25	8.790
Y5	7 - 8	1.0	7.60	7.560
E5	600 - 1100	500.0	750.00	1029.000

Net benefit = Rs.117.18 x 10^7

I, Y are in MAF and E is in million kwhr.

TABLE 6.3.5. RESULTS OF STEEPEST ASCENT METHOD FOR SAMPLE 5

Variable	Assumed limits of variable	Range	Starting base value	Final value
1	2	3	4	5
I1	2 - 5	3.0	2.60	4.000
Y1	3 - 7	4.0	6.50	5.640
E1	50 - 150	100.0	90.00	68.000
I2	5 - 13	8.0	8.50	9.600
Y2	10 - 16	6.0	14.00	13.740
E2	600 - 1000	1000.0	685.00	2085.000
I3	2 - 5	3.0	3.00	3.760
Y3	0.5 - 2.0	1.5	1.50	1.440
E3	600 - 1000	400.0	750.00	900.000
Y4	0.3 - 0.7	0.4	0.42	0.418
E4	200 - 600	400.0	350.00	529.000
I5	7 - 10	3.0	8.50	8.970
Y5	7 - 8	1.0	7.70	7.660
E5	600 - 1100	500.0	775.00	1053.000

Net benefit = Rs.118.16 x 10^7

I, Y are in MAF. and E is in million kwhr.

TABLE 6.3.6. RESULTS OF STEEPEST ASCENT METHOD FOR SAMPLE 6

Variable	Assumed limits of variable	Range	Starting base value	Final value
1	2	3	4	5
I1	2 - 5	3.0	2.60	4.007
Y1	3 - 7	4.0	6.75	5.940
E1	50 - 150	100.0	95.00	73.000
I2	5 - 13	8.0	8.75	9.670
Y2	10 - 16	6.0	14.50	14.280
E2	600 - 1600	1000.0	700.00	2100.000
I3	2 - 5	3.0	3.25	4.000
Y3	0.5 - 2.0	1.5	1.65	1.623
E3	600 - 1000	400.0	775.00	923.000
Y4	0.3 - 0.7	0.4	0.41	0.409
E4	200 - 600	400.0	375.00	550.000
I5	7 - 10	3.0	8.75	9.150
Y5	7 - 8	1.0	7.80	7.760
E5	600 - 1100	500.0	800.00	1078.000

Net benefit = Rs.119.34 x 10^7

I, Y are in MAF and E is in million kwhr.

TABLE 6.3.7. RESULTS OF STEEPEST ASCENT METHOD FOR SAMPLE 7

Variable	Assumed limits of variable	Range	Starting base value	Final value
1	2	3	4	5
I1	2 - 5	3.0	2.75	4.09
Y1	3 - 7	4.0	7.00	6.24
E1	50 - 150	100.0	100.00	78.30
I2	5 - 13	8.0	9.50	9.86
Y2	10 - 16	6.0	15.00	14.82
E2	600 - 1600	1000.0	700.00	2100.00
I3	2 - 5	3.0	3.40	4.14
Y3	0.5 - 2.0	1.5	1.65	1.62
E3	600 - 1000	400.0	800.00	945.00
Y4	0.3 - 0.7	0.4	0.45	0.44
E4	200 - 600	400.0	400.00	570.30
I5	7 - 10	3.0	9.25	9.52
Y5	7 - 8	1.0	7.80	7.76
E5	600 - 1100	500.0	825.00	1101.00

Net benefit = Rs.120.50 x 10^7

I, Y are in MAF. and E is in million kwhr.

TABLE 6.3.8. RESULTS OF STEEPEST ASCENT METHOD FOR SAMPLE 8

Variable	Assumed limits of variable	Range	Starting base value	Final value
1	2	3	4	5
I1	2 - 5	3.0	3.00	4.24
Y1	3 - 7	4.0	7.00	6.24
E1	50 - 150	100.0	100.00	78.30
I2	5 - 13	8.0	9.00	9.73
Y2	10 - 16	6.0	15.00	14.82
E2	600 - 1600	1000.0	700.00	2100.00
I3	0.2 - 5	3.0	3.40	4.14
Y3	0.5 - 2.0	1.5	1.75	1.74
E3	600 - 1000	400.0	800.00	945.00
Y4	0.3 - 0.7	0.4	0.40	0.40
E4	200 - 600	400.0	400.00	570.00
I5	7 - 10	3.0	9.00	9.34
Y5	7 - 8	1.0	7.70	7.66
E5	600 - 1100	500.0	825.00	1101.00

Net benefit = Rs. 120.64×10^7

I, Y are in MAF and E is in million kwhr.

TABLE 6.3.9. RESULTS OF STEEPEST ASCENT METHOD FOR SAMPLE 9

Variable	Assumed limits of variable	Range	Starting base value	Final value
1	2	3	4	5
I1	2 - 5	3.0	2.60	4.00
Y1	3 - 7	4.0	7.00	6.24
E1	50 - 150	100.0	100.00	78.30
I2	5 - 13	8.0	10.00	10.29
Y2	10 - 16	6.0	15.00	14.82
E2	600 - 1600	1000.0	700.00	2100.00
I3	2 - 5	3.0	3.40	4.14
Y3	0.5 - 2.0	1.5	1.65	1.62
E3	600 - 1000	400.0	800.00	945.00
Y4	0.3 - 0.7	0.4	0.41	0.41
E4	200 - 600	400.0	425.00	590.00
I5	7 - 10	3.0	9.25	9.52
Y5	7 - 8	1.0	7.80	7.76
E5	600 - 1100	500.0	825.00	1101.00

Net benefit = Rs.120.65 x 10^7

I, Y are in MAF and E is in million kwhr.

TABLE 6.3.10. FINAL SELECTED SET OF VARIABLES

Sl. No.	Variable	Selected value
1	I1	4.00
2	Y1	6.24
3	E1	78.30 (9 MW)
4	I2	10.30
5	Y2	14.82
6	E2	2100.00 (240 MW)
7	I3	4.14
8	Y3	1.62
9	E3	945.00 (108 MW)
10	Y4	0.41
11	E4	590.00 (67 MW)
12	I5	9.52
13	Y5	7.76
14	E5	1100.00 (125 MW)

I, Y are in MAF and E is in million kwhr.

in storage for use later for irrigation and other beneficial purposes. A well co-ordinated plan is generally, required to be developed by considering demands for the various purposes and distribution of releases among various reservoirs.

An operating policy showing releases for each reservoir (Tables 5.3.14 to 5.3.16) and the minimum and maximum permissible storages at the end of each month for each reservoir (Tables 5.3.17 to 5.3.19) are adopted and simulation carried out. A separate flood release policy is assumed for flood month (Table 5.3.5). Ten simulation runs are carried out for various cases mentioned in Section 5.6.

The results of simulation studies are given under the following groups.

6.4.1. Annual irrigation shortages

Under the operating policy adopted, the performance of the system is evaluated in terms of irrigation and power shortages. Tables 6.4.1 to 6.4.10 shows annual irrigation shortages and their frequencies in terms of "types" of shortages. The "types" of shortages have already been described in Section 5.4. Table 6.4.1 refers to the irrigation shortages for twenty eight years of historical streamflows data for modified NWDT award (modification as explained in Section 5.4). Tables 6.4.2 to 6.4.4 refer to irrigation shortages using fifty years each of synthetic flows for modified NWDT award. Similar results for the cases incorporating the NWDT award (see extract in Appendix) are given in Tables 6.4.5 to 6.4.8. The Table 6.4.9 and 6.4.10 refer to flood studies.

TABLE 6.4.1. TYPES OF ANNUAL IRRIGATION SHORTAGES AND THEIR FREQUENCIES FOR 28 YEARS OF HISTORICAL FLOWS FOR MODIFIED NWDT AWARD

Reservoir No.	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	Type 8	Type 9	Type 10	Type 11
1	2	3	4	5	6	7	8	9	10	11	12
1	26	0	0	0	0	0	0	2	0	0	0
2	19	3	0	1	0	0	1	0	1	0	3
3	20	1	1	1	0	0	1	0	1	0	3
4	0	0	0	0	0	0	0	0	0	0	0
5	9	0	0	8	6	0	4	0	1	0	0

TABLE 6.4.2. TYPES OF ANNUAL IRRIGATION SHORTAGES AND THEIR FREQUENCIES FOR THE FIRST 50 YEARS O SYNTHETIC FLOWS FOR MODIFIED NWDT AWARD

Reservoir No.	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	Type 8	Type 9	Type 10	Type 11
1	2	3.	4	5	6	7	8	9	10	11	12
1	45	1	3	0	0	0	0	0	0	1	0
2	23	1	5	1	4	0	3	0	3	0	10
3	25	0	4	2	4	0	2	0	5	0	8
4	0	0	0	0	0	0	0	0	0	0	0
5	12	1	3	7	10	1	13	2	0	0	1

TABLE 6.4.3. TYPES OF ANNUAL IRRIGATION SHORTAGES AND THEIR FREQUENCIES FOR THE SECOND 50 YEARS SYNTHETIC FLOWS FOR MODIFIED NWDT AWARD

Reser-voir No.	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	Type 8	Type 9	Type 10	Type 11
1	2	3	4	5	6	7	8	9	10	11	12
1	48	0	1	0	0	0	0	1	0	0	0
2	29	3	1	2	3	0	3	0	0	0	9
3	31	1	0	3	3	0	1	0	4	1	6
4	0	0	0	0	0	0	0	0	0	0	0
5	19	1	1	5	10	1	11	2	0	0	0

TABLE 6.4.4. TYPES OF ANNUAL IRRIGATION SHORTAGES AND THEIR FREQUENCIES FOR THE THIRD 50 YEARS SYNTHETIC FLOWS FOR MODIFIED NWDT AWARD

Reservoir No.	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	Type 8	Type 9	Type 10	Type 11
1	2	3	4	5	6	7	8	9	10	11	12
1	44	0	3	1	0	1	0	1	0	0	0
2	32	1	1	4	1	0	1	0	0	0	10
3	32	1	1	4	0	0	1	0	2	0	9
4	0	0	0	0	0	0	0	0	0	0	0
5	25	1	2	1	7	0	11	1	0	1	1

TABLE 6.4.5. TYPES OF ANNUAL IRRIGATION SHORTAGES AND THEIR FREQUENCIES FOR 28 YEARS OF HISTORICAL FLOWS FOR NWDT AWARD

Reser-voir No.	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	Type 8	Type 9	Type 10	Type 1
1	2	3	4	5	6	7	8	9	10	11	12
1	24	2	0	0	0	0	0	2	0	0	0
2	24	2	0	0	0	0	0	0	0	0	2
3	24	2	1	0	0	0	0	0	0	0	1
4	0	0	0	0	0	0	0	0	0	0	0
5	11	1	3	3	5	0	3	1	1	0	0

TABLE 6.4.6. TYPES OF ANNUAL IRRIGATION SHORTAGES AND THEIR FREQUENCIES FOR THE FIRST 50 YEARS SYNTHETIC FLOWS FOR NWDT AWARD

Reservoir No.	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	Type 8	Type 9	Type 10	Type 11
1	2	3	4	5	6	7	8	9	10	11	12
1	45	2	0	2	0	0	0	0	0	0	1
2	31	5	2	3	1	0	1	0	3	0	4
3	33	2	5	4	1	1	3	0	1	0	0
4	0	0	0	0	0	0	0	0	0	0	0
5	18	6	2	7	5	0	7	4	0	0	1

TABLE 6.4.7. TYPES OF ANNUAL IRRIGATION SHORTAGES AND THEIR FREQUENCIES FOR THE SECOND 50 YEAR SYNTHETIC FLOWS FOR NWDT AWARD

Reservoir No.	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	Type 8	Type 9	Type 10	Type 1
1	2	3	4	5	6	7	8	9	10	11	12
1	43	1	1	3	0	0	0	2	0	0	0
2	29	4	2	5	1	1	4	0	0	0	4
3	27	11	2	3	3	0	3	0	0	0	1
4	0	0	0	0	0	0	0	0	0	0	0
5	19	0	2	10	7	1	8	2	1	0	0

TABLE 6.4.8. TYPES OF ANNUAL IRRIGATION SHORTAGES AND THEIR FREQUENCIES FOR THE THIRD 50 YEARS SYNTHETIC FLOWS FOR NWDT AWARD

Reser-voir No.	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	Type 8	Type 9	Type 10	Type 11
1	2	3	4	5	6	7	8	9	10	11	12
1	43	2	0	3	0	0	0	2	0	0	0
2	36	2	2	2	1	0	2	0	3	0	2
3	35	8	2	2	2	0	1	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0
5	15	5	3	9	6	0	11	1	0	0	0

TABLE 6.4.9. TYPES OF ANNUAL IRRIGATION SHORTAGES AND THEIR FREQUENCIES FOR FLOOD SIMULATION FOR 28 YEARS OF HISTORICAL FLOWS FOR NWDT AWARD

Reservoir No.	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	Type 8	Type 9	Type 10	Type 11
1	2	3	4	5	6	7	8	9	10	11	12
1	24	2	0	0	0	0	0	2	0	0	0
2	24	1	0	0	1	0	0	0	0	0	2
3	23	2	2	0	0	0	0	0	0	0	1
4	0	0	0	0	0	0	0	0	0	0	0
5	16	1	2	2	3	0	2	1	1	0	0

TABLE 6.4.10. TYPES OF ANNUAL IRRIGATION SHORTAGES AND THEIR FREQUENCIES FOR FLOOD SIMULATION FOR 28 YEARS OF HISTORICAL FLOWS FOR MODIFIED NWDT AWARD

Reservoir No.	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	Type 8	Type 9	Type 10	Type 11
1	2	3	4	5	6	7	8	9	10	11	12
1	26	0	0	0	0	0	0	2	0	0	0
2	21	2	0	0	0	0	2	0	0	0	3
3	21	2	0	0	0	0	2	0	0	0	3
4	0	0	0	0	0	0	0	0	0	0	0
5	14	0	2	1	6	0	3	0	1	1	0

6.4.2. Power shortages

Two seasons (July to September, and, October to June) are considered for finding the actual power production and shortages during each simulation study. The types of power shortages have been described for each season in Section 5.4. Table 6.4.11 refers to power shortages for each season for twenty eight years of historical streamflow data for modified NWDT award. Tables 6.4.12 to 6.4.14 refer to power shortages for fifty years each of generated data for modified NWDT award. Similar results for the cases incorporating the NWDT award are given in Tables 6.4.15 to 6.4.18. Tables 6.4.19 and 6.4.20 refer to flood studies.

6.4.3. Shortage index

Another method of indicating the shortages by a "shortage index" as defined by Beard (see Section 5.5) is also incorporated in the simulation program. The shortage indices for various simulation runs are given in Tables 6.4.21 to 6.4.30 Shortage index for canal (irrigation) are found to be higher at each reservoir site. Suppose canal (irrigation) shortage index 5 occurs for a 50-year simulation period, one can say that there may be 10 annual shortages of 50% each, or 20 annual shortages of about 36% each, or 50 annual shortages of about 22% each, etc. in a 50 year period. One cannot say whether shortages occurred consecutively or not.

TABLE 6.4.11. TYPES OF POWER SHORTAGES AND THEIR FREQUENCIES FOR EACH SEASON FOR 28 YEARS OF HISTORICAL FLOWS FOR MODIFIED NWDT AWARD

Reservoir No.	Seasonal power shortages												Remarks
	July to September Season 1						October to June Season 2						
	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	74	0	2	2	2	4	242	0	0	0	0	10	CHPH
2	80	1	0	0	0	3	210	0	0	0	0	42	RBPH
3	83	0	0	0	0	1	202	4	2	0	0	44	RBPH
4	82	0	0	0	0	2	161	0	0	0	0	91	RBPH
5	28	0	1	23	11	21	165	0	0	0	0	87	CHPH

TABLE 6.4.12. TYPES OF POWER SHORTAGES AND THEIR FREQUENCIES FOR EACH SEASON FOR 50 YEARS OF SYNTHETIC FLOWS FOR MODIFIED NWDT AWARD

Reservoir No.	Seasonal power shortages												Remarks
	July to September Season 1						October to June Season 2						
	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	122	3	4	2	3	16	422	0	0	0	0	28	CHPH
2	141	2	0	0	0	7	304	0	0	0	0	146	RBPH
3	148	0	0	0	0	2	300	4	2	0	0	144	RBPH
4	148	0	1	0	0	1	213	0	0	0	0	237	RBPH
5	50	0	1	37	22	40	257	0	0	0	0	193	CHPH

TABLE 6.4.13. TYPES OF POWER SHORTAGES AND THEIR FREQUENCIES FOR EACH SEASON FOR 50 YEARS OF SYNTHETIC FLOWS FOR MODIFIED NWDT AWARD

Reservoir No.	Seasonal power shortages												Remarks
	July to September Season 1						October to June Season 2						
	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	126	7	3	1	2	11	437	0	1	1	0	11	CHPH
2	139	0	1	1	1	8	335	0	0	0	0	115	RBPH
3	148	0	0	0	0	2	332	4	1	0	0	113	RBPH
4	146	0	1	1	0	2	258	0	0	0	0	192	RBPH
5	50	0	1	44	27	28	290	0	0	0	0	160	CHPH

TABLE 6.4.14. TYPES OF POWER SHORTAGES AND THEIR FREQUENCIES FOR EACH SEASON FOR 50 YEARS OF SYNTHETIC FLOWS FOR MODIFIED NWDT AWARD

Reservoir No.	Seasonal power shortages												Remarks
	July to September Season 1						October to June Season 2						
	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	119	6	2	6	0	17	425	0	0	0	0	25	CHPH
2	137	0	1	0	0	12	338	0	0	0	0	112	RBPH
3	144	0	0	0	0	6	335	4	1	1	0	109	RBPH
4	144	0	1	0	0	5	283	0	0	0	0	167	RBPH
5	50	0	3	39	20	38	314	0	0	0	0	136	CHPH

TABLE 6.4.15. TYPES OF POWER SHORTAGES AND THEIR FREQUENCIES FOR EACH SEASON FOR 28 YEARS OF HISTORICAL FLOWS FOR NWDT AWARD

Reservoir No.	Seasonal power shortages												Remarks
	July to September Season 1						October to June Season 2						
	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	61	2	1	0	2	18	236	0	0	0	0	16	CHPH
2	81	0	2	0	0	1	223	0	0	0	0	29	RBPH
3	83	0	0	0	0	1	221	0	0	1	0	30	RBPH
4	84	0	0	0	0	0	170	0	0	0	0	82	RBPH
5	49	2	2	4	1	26	163	0	0	0	0	89	CHPH

TABLE 6.4.16. TYPES OF POWER SHORTAGES AND THEIR FREQUENCIES FOR EACH SEASON FOR 50 YEARS OF SYNTHETIC FLOWS FOR NWDT AWARD

Reservoir No.	Seasonal power shortages												Remarks
	July to September Season 1						October to June Season 2						
	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	101	3	2	4	3	37	430	0	0	0	0	20	CHPH
2	143	1	0	0	0	6	336	0	0	0	0	115	RBPH
3	147	0	0	0	0	3	351	2	5	2	2	88	RBPH
4	148	0	0	0	0	2	228	0	0	0	0	222	RBPH
5	68	7	2	9	10	54	293	0	0	0	0	157	CHPH

TABLE 6.4.17. TYPES OF POWER SHORTAGES AND THEIR FREQUENCIES FOR EACH SEASON FOR 50 YEARS OF SYNTHETIC FLOWS FOR NWDT AWARD

Reservoir No.	Seasonal power shortages												Remarks
	July to September Season 1						October to June Season 2						
	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	119	3	1	3	5	19	423	1	0	0	0	26	CHPH
2	142	0	0	0	0	8	356	1	0	0	0	93	RBPH
3	148	0	0	0	0	2	374	0	1	0	0	75	RBPH
4	149	0	0	0	0	1	269	0	0	0	0	181	RBPH
5	82	4	11	6	5	42	271	0	0	0	0	179	CHPH

TABLE 6.4.18. TYPES OF POWER SHORTAGES AND THEIR FREQUENCIES FOR EACH SEASON FOR 50 YEARS OF SYNTHETIC FLOWS FOR NWDT AWARD

Reservoir No.	Seasonal power shortages												Remarks
	July to September Season 1						October to June Season 2						
	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	107	3	5	1	1	33	423	0	0	0	1	26	CHPH
2	142	1	0	1	0	6	341	0	0	0	0	109	RBPH
3	143	0	0	0	0	7	385	1	2	0	1	61	RBPH
4	144	0	0	1	0	5	294	0	0	0	0	156	RBPH
5	88	3	3	4	5	47	306	0	0	0	0	144	CHPH

TABLE 6.4.20. TYPES OF POWER SHORTAGES AND THEIR FREQUENCIES FOR EACH SEASON FOR FLOOD SIMULATION FOR 28 YEARS OF HISTORICAL FLOWS FOR MODIFIED NWDT AWARD

Reservoir No.	Seasonal power shortages												Remarks
	July to September Season 1						October to June Season 2						
	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	74	0	2	2	2	4	242	0	0	0	0	10	CHPH
2	81	0	0	0	0	3	214	0	0	0	0	38	RBPH
3	83	0	0	0	0	1	206	4	2	0	0	40	RBPH
4	82	0	0	0	0	2	171	0	0	0	0	81	RBPH
5	34	0	6	22	2	20	167	0	0	0	0	85	CHPH

6.4.4. Averages

For each simulation run, average monthly results are obtained and shown in Tables 6.4.21 to 6.4.30. For instance Table 6.4.21 shows the average monthly results for twenty eig[h]t years of historical flows. In this table, column (2) shows the regenerated flow due to upstream uses (other than command area under a particular reservoir), column (3) the regenerated flow caused due to water uses under immediate upstream reservoir, column (4) the inflow due to independent catchment area, column (5) the release from upstream reservoir, column (6), column (7), and column (8) the required release for irrigation actual release, and shortages respectively. column (9) the upstream water requirements above a particular reservoir, column (10), column (11), and column (12) required release to downstream, actual release and shortages respectively. The shortage mentioned in column (12) has not the same meaning as that for irrigation shortages in column (8) because in calculating river shortages, negative shortages are set equal to zero. Similar results for power are shown in Tables 6.4.31 to 6.4.40.

6.4.5. Rigid rules

Another output of the simulation consists of the end of month storages which can be used for the development of rigid rules for each reservoir. End of month storages are obtained for each hydrological state of basin like very wet, wet, average and dry. The mean value for each month is calculated and are tabulated in Tables 6.4.41 to 6.4.50. The graphs of mean end

TABLE 6.4.21. AVERAGE MONTHLY RESULTS FOR 28 YEARS HISTORICAL FLOWS FOR MODIFIED NWDT AWARD (Flows in cfs)

Reservoir No.	Regenerated flow due to upstream use of water	Regenerated flow due to area under upstream reservoir control	Inflow	Release from upstream reservoir	Release to canal			Upstream water requirement	Release to river		
					Req	Actual	Shortage		Req	Actual	Shortage*
1	2	3	4	5	6	7	8	9	10	11	12
1	296	0	9343	0	3173	3088	85	2277	620	3733	2
2	1594	396	25316	3733	1800	1571	229	12494	9777	15849	640
3	0	227	1785	15849	1568	1372	196	0	10397	16501	689
4	185	196	1877	16500	0	0	0	1446	10538	17287	848
5	354	0	6238	17287	13152	10317	2775	2703	23	9866	5

Reservoir - 1	Reservoir - 2	Reservoir - 3	Reservoir - 4	Reservoir - 5
Canal shortage index = 1.021	Canal shortage index = 8.30	Canal shortage index = 7.97	Canal shortage index = 0.000	Canal shortage index = 7.00
D/S requirement shortage index = 3.02	D/S requirement shortage index = 2.38	D/S requirement shortage index = 1.08	D/S requirement shortage index = 1.30	D/S requirement shortage index = 5.74

*In calculating shortages in column (12), negative shortages are set to zero.

TABLE 6.4.22. AVERAGE MONTHLY RESULTS FOR 50 YEARS SYNTHETIC FLOWS FOR MODIFIED NWDT AWARD (Flows in cfs)

Reservoir No.	Regenerated flow due to upstream use of water	Regenerated flow due to area under upstream reservoir control	Inflow	Release from upstream reservoir	Release to canal			Upstream water requirement	Release to river		
					Req	Actual	Shortage		Req	Actual	Shortage
1	2	3	4	5	6	7	8	9	10	11	12
1	309	0	8691	0	3169	3045	124	2273	620	3243	02
2	1658	396	20621	3243	1816	1397	419	12469	9768	11485	829
3	0	227	1448	11485	1566	1223	343	0	10387	11862	1097
4	193	196	1663	11862	0	0	0	1443	10538	12498	1222
5	370	0	6188	12498	13136	9672	3464	2696	23	5877	06

Reservoir - 1	Reservoir - 2	Reservoir - 3	Reservoir - 4	Reservoir - 5
Canal shortage index = 1.378	Canal shortage index = 13.73	Canal shortage index = 12.16	Canal shortage index = 0.000	Canal shortage index = 8.59
D/S requirement shortage index = 0.013	D/S requirement shortage index = 2.38	D/S requirement shortage index = 1.89	D/S requirement shortage index = 1.93	D/S requirement shortage index = 6.74

*In calculating shortages in column (12), negative shortages are set to zero.

TABLE 6.4.23. AVERAGE MONTHLY RESULTS FOR 50 YEARS SYNTHETIC FLOWS FOR MODIFIED NWDT AWARD (Flows in cfs)

Reservoir No.	Regenerated flow due to upstream use of water	Regenerated flow due to area under upstream reservoir control	Inflow	Release from up-stream reservoir	Release to canal			Up-stream water requirement	Release to river		
					Req	Actual	Shortage		Req	Actual	Shortage*
1	2	3	4	5	6	7	8	9	10	11	12
1	305	0	9400	0	3172	3126	46	2278	620	3827	1
2	1643	396	22976	3827	1817	1489	329	12499	9778	13922	704
3	0	227	1617	13922	1567	1303	265	0	10395	14365	873
4	191	196	1760	14365	0	0	0	1446	10538	15023	1014
5	365	0	6830	15023	13149	10328	2820	2704	23	8432	4

Reservoir - 1	Reservoir - 2	Reservoir - 3	Reservoir - 4	Reservoir - 5
Canal shortage index = 0.435	Canal shortage index = 10.18	Canal shortage index = 8.8	Canal shortage index = 0.000	Canal shortage index = 6.89
Downstream requirement shortage index = 0.005	Downstream requirement shortage index = 1.54	Downstream requirement shortage index = 1.37	Downstream requirement shortage index = 1.65	Downstream requirement shortage index = 5.37

*In calculating shortages negative shortages are set to zero in column(12.)

TABLE 6.4.24. AVERAGE MONTHLY RESULTS FOR 50 YEARS SYNTHETIC FLOWS FOR MODIFIED NWDT AWARD (Flows in cfs)

Rese-rvoir No.	Regenerated flow due to upstream use of water	Regenerated flow due to area under upstream reservoir control	Inflow	Release from up-stream reser-voir	Release to canal			Up-stream water requi-rement	Release to river		
					Req	Actual	Shor-tage		Req	Actual	Shor-tage*
1	2	3	4	5	6	7	8	9	10	11	12
1	309	0	9252	0	3173	3079	95	2278	620	3718	2
2	1657	396	25239	3718	1818	1487	331	12497	9778	15993	903
3	0	227	1781	15993	1568	1300	268	0	10398	16630	952
4	193	196	1904	16630	0	0	0	1446	10538	17563	979
5	370	0	6954	17563	13153	10684	2469	2704	23	10710	4

Reservoir - 1
Canal shortage index = 0.756
Downstream requirement shortage index = 0.008

Reservoir - 2
Canal shortage index = 11.79
Downstream requirement shortage index = 3.89

Reservoir - 3
Canal shortage index = 10.24
Downstream requirement shortage index = 2.588

Reservoir - 4
Canal shortage index = 0.000
Downstream requirement shortage index = 2.113

Reservoir - 5
Canal shortage index = 6.73
Downstream requirement shortage index = 5.84

*In calculating shortages negative shortages are set to zero in column (12.)

TABLE 6.4.25. AVERAGE MONTHLY RESULTS FOR 28 YEARS OF HISTORICAL FLOWS FOR NWDT AWARD (Flows in cfs)

Reservoir No.	Regenerated flow due to upstream use of water	Regenerated flow due to area under upstream reservoir control	Inflow	Release from upstream reservoir	Release to canal			Upstream water requirement	Release to river		
					Req	Actual	Shortage		Req	Actual	Shortage
1	2	3	4	5	6	7	8	9	10	11	12
1	308	0	9343	0	3512	3322	190	2538	1270	3262	63
2	1538	438	25316	3262	2263	2234	28	12837	10223	14273	186
3	0	284	1785	14273	1871	1845	25	0	10646	14309	366
4	211	233	1877	14309	0	0	0	1765	10538	14781	741
5	361	0	6238	14781	13981	10749	3232	2949	23	6742	5

Reservoir - 1	Reservoir - 2	Reservoir - 3	Reservoir - 4	Reservoir - 5
Canal shortage index = 1.29	Canal shortage index = 4.38	Canal shortage index = 3.66	Canal shortage index = 0.00	Canal shortage index = 6.12
Downstream requirement shortage index = 3.47	Downstream requirement shortage index = 0.54	Downstream requirement shortage index = 0.30	Downstream requirement shortage index = 0.97	Downstream requirement shortage index = 5.22

*In calculating shortages negative shortages are set to zero in column (12)

TABLE 6.4.26. AVERAGE MONTHLY RESULTS FOR 50 YEARS SYNTHETIC FLOWS FOR NWDT AWARD (Flows in cfs)

Reser-voir No.	Regenerated flow due to upstream use of water	Regenerated flow due to area under upstream reservoir control	Inflow	Release from up-stream reser-voir	Release to canal			Up-stream water requi-rement	Release to river		
					Req	Actual	Shor-tage		Req	Actual	Shor tage
1	2	3	4	5	6	7	8	9	10	11	12
1	273	0	8691	0	3220	3110	110	2175	1030	3212	34
2	1533	402	20621	3212	1862	1713	148	12526	9806	10668	483
3	0	233	1448	10668	1528	1445	83	0	10316	10832	809
4	173	191	1663	10832	0	0	0	1399	10538	11410	1148
5	328	0	6188	11410	12993	9855	3138	2600	23	4680	5

Reservoir - 1	Reservoir - 2	Reservoir - 3	Reservoir - 4	Reservoir - 5
Canal shortage index = 0.92	Canal shortage index = 6.175	Canal shortage index = 1.90	Canal shortage index = 0.000	Canal shortage index = 6.62
Downstream requirement shortage index = 0.65	Downstream requirement shortage index = 1.055	Downstream requirement shortage index = 0.85	Downstream requirement shortage index = 1.47	Downstream requirement shortage index = 5.63

*In calculating shortages negative shortages are set to zero in column (12).

TABLE 6.4.27. AVERAGE MONTHLY RESULTS FOR 50 YEARS SYNTHETIC FLOWS FOR NWDT AWARD (Flows in cfs)

Reser-voir No.	Regenerated flow due to upstream use of water	Regenerated flow due to area under upstream reservoir control	Inflow	Release from up-stream reser-voir	Release to canal			Up-stream water requir-ements	Release to river		
					Req	Actual	Shor-tage		Req	Actual	Sho tag
1	2	3	4	5	6	7	8	9	10	11	12
1	340	0	9400	0	3553	3378	175	2547	1247	3370	66
2	1685	444	22976	3370	2227	2081	146	12868	10186	12387	424
3	0	278	1617	12387	1867	1773	94	0	10676	12411	675
4	227	233	1760	12411	0	0	0	1742	10538	12852	885
5	401	0	6830	12852	14082	10332	3751	2969	23	5848	5

Reservoir - 1
Canal shortage index = 0.98
Downstream requirement shortage index = 0.61

Reservoir - 2
Canal shortage index = 5.64
Downstream requirement shortage index = 0.69

Reservoir - 3
Canal shortage index = 2.00
Downstream requirement shortage index = 0.65

Reservoir - 4
Canal shortage index = 0.000
Downstream requirement shortage index = 0.99

Reservoir - 5
Canal shortage index = 7.92
Downstream requirement shortage index = 6.61

*In calculating shortages negative shortages are set to zero in column (12)

TABLE 6.4.29. AVERAGE MONTHLY RESULTS FOR FLOOD SIMULATION FOR 28 YEARS OF HISTORICAL FLOWS FOR NWDT AWARD
(Flows in cfs)

Reservoir No.	Regenerated flow due to upstream use of water	Regenerated flow due to area under upstream reservoir control	Inflow	Release from up-stream reservoir	Release to canal			Up-stream water requirement	Release to river		
					Req	Actual	Shortage		Req	Actual	Shortage*
1	2	3	4	5	6	7	8	9	10	11	12
1	308	0	9343	0	3512	3322	190	2538	1270	3262	63
2	1836	437	25166	3296	2276	2242	34	12838	9451	15401	190
3	0	294	1773	15401	1872	1822	50	0	9308	19259	350
4	252	242	1870	19259	0	0	0	1767	9206	20586	582
5	449	0	6253	20536	14104	12081	2024	2949	1818	13185	6

Reservoir - 1	Reservoir - 2	Reservoir - 3	Reservoir - 4	Reservoir - 5
Canal shortage index = 1.287	Canal shortage index = 4.566	Canal shortage index = 3.826	Canal shortage index = 0.000	Canal shortage index = 3.35
Downstream requirement shortage index = 0.650	Downstream requirement shortage index = 0.460	Downstream requirement shortage index = 0.311	Downstream requirement shortage index = 0.83	Downstream requirement shortage index = 1.05

*In calculating shortages negative shortages are set to zero in column (12)

TABLE 6.4.30. AVERAGE MONTHLY RESULTS FOR FLOOD SIMULATION FOR 28 YEARS OF HISTORICAL FLOWS FOR MODIFIED NWDT AWARD
(Flows in cfs)

Reservoir No.	Regenerated flow due to upstream use of water	Regenerated flow due to area under upstream reservoir control	Inflow	Release from upstream reservoir	Release to canal			Upstream water requirement	Release to river		
					Req	Actual	Shortage		Req	Actual	Shortage*
1	2	3	4	5	6	7	8	9	10	11	12
1	296	0	9343	0	3173	3088	85	2277	620	3733	2
2	1770	406	25166	3733	1870	1664	206	12637	9054	16502	587
3	0	251	16502	16502	1630	1453	177	0	9138	17170	626
4	239	217	1870	17170	0	0	0	1589	9224	18154	786
5	428	0	6253	18154	13216	10485	2731	2857	1816	11860	27

Reservoir - 1	Reservoir - 2	Reservoir - 3	Reservoir - 4	Reservoir - 5
Canal shortage index = 1,021	Canal shortage index = 7.92	Canal shortage index = 7.58	Canal shortage index = 0.000	Canal shortage index = 6,45
Downstream requirement shortage index = 0.009	Downstream requirement shortage index = 2.27	Downstream requirement shortage index = 1.01	Downstream requirement shortage index = 1.30	Downstream requirement shortage index = 3.18

*In calculating shortages negative shortages are set to zero in column (12)

TABLE 6.4.31. AVERAGE SEASONAL ENERGY FOR 28 YEARS OF HISTORICAL FLOWS FOR MODIFIED NWDT AWARD

Reservoir No.	Seasonal energy in 1000 kwhr						Remarks
	July to September			October to June			
	Req +	Actual	Shortage*	Req +	Actual	Shortage*	
1	2	3	4	5	6	7	8
1	11858	15366	547	3953	7276	157	CHPH
2	316244	554580	11549	19764	31568	3294	RBPH
3	142301	262088	1694	19764	29431	3503	RBPH
4	88279	158798	1422	19764	24217	7121	RBPH
5	164700	165159	29626	19764	24803	6823	CHPH

	Reservoir 1		Reservoir 2		Reservoir 3		Reservoir 4		Reservoir 5	
	July to Sept	Oct to June	July to Sept	Oct to June	July to Sept	Oct to June	July to Sept	Oct to June	July to Sept	Oct to June
Power shortage index	0.630	2.20	1.19	13.84	0.40	14.00	0.43	24.00	3.89	17.50

* In calculating shortages, negative shortages are set to zero.

+ Load factor = 60%.

TABLE 6.4.32. AVERAGE SEASONAL ENERGY FOR 50 YEARS OF SYNTHETIC FLOWS FOR MODIFIED NWDT AWARD

Reservoir No.	Seasonal energy in 1000 kwhr						Remarks
	July to September			October to June			
	Req+	Actual	Shortage*	Req+	Actual	Shortage*	
1	2	3	4	5	6	7	8
1	11858	14827	729	3953	7105	241	CHPH
2	316224	534376	14606	19764	25541	6390	RBPH
3	142301	259155	1897	19764	23795	6339	RBPH
4	88279	157595	769	19764	17930	10409	RBPH
5	164700	164019	29404	19764	21634	8477	CHPH

	Reservoir 1		Reservoir 2		Reservoir 3		Reservoir 4		Reservoir 5	
	July to Sept	Oct to June	July to Sept	Oct to June	July to Sept	Oct to June	July to Sept	Oct to June	July to Sept	Oct to June
Power shortage index	1.003	2.92	1.475	24.61	0.444	22.86	0.231	37.00	3.64	21.60

*In calculating shortages, negative shortages are set to zero.

+Load factor = 60%.

TABLE 6.4.33. AVERAGE SEASONAL ENERGY FOR 50 YEARS OF SYNTHETIC FLOWS FOR MODIFIED NWDT AWARD

Reservoir No.	Seasonal energy in 1000 kwhr						Remarks
	July to September			October to June			
	Req +	Actual	Shortage*	Req +	Actual	Shortage*	
1	2	3	4	5	6	7	8
1	11858	15405	543	3953	7364	95	CHPH
2	316224	544665	16785	19764	28182	5000	RBPH
3	142301	261870	1897	19764	26803	5007	RBPH
4	88279	159297	1380	19764	21805	8346	RBPH
5	164700	167539	27434	19764	24412	7027	CHPH

	Reservoir 1		Reservoir 2		Reservoir 3		Reservoir 4		Reservoir 5	
	July to Sept	Oct to June	July to Sept	Oct to June	July to Sept	Oct to June	July to Sept	Oct to June	July to Sept	Oct to June
Power shortage index	0.826	1.036	1.61	18.40	0.44	17.66	0.46	29.50	3.14	18.00

* In calculating shortage, negative shortages are set to zero.

\+ Load factor = 60%.

TABLE 6.4.34. AVERAGE SEASONAL ENERGY FOR 50 YEARS OF SYNTHETIC FLOWS FOR MODIFIED NWDT AWARD

Reservoir No.	Seasonal energy in 1000 kwhr						Remarks
	July to September			October to June			
	Req +	Actual	Shortage*	Req +	Actual	Shortage*	
1	2	3	4	5	6	7	8
1	11858	15156	688	3953	7165	207	CHPH
2	316224	533121	19312	19764	27738	4919	RBPH
3	142301	255294	5497	19764	27591	4825	RBPH
4	88279	156077	3046	19764	23848	7309	RBPH
5	164700	165758	28903	19764	26433	5973	CHPH

	Reservoir 1		Reservoir 2		Reservoir 3		Reservoir 4		Reservoir 5	
	July to Sept	Oct to June	July to Sept	Oct to June	July to Sept	Oct to June	July to Sept	Oct to June	July to Sept	Oct to June
Power shortage index	1.075	2.044	2.124	19.75	1.250	18.40	1.114	28.33	3.551	16.15

* In calculating shortages, negative shortages are set to zero.

+ Load factor = 60%.

TABLE 6.4.35. AVERAGE SEASONAL ENERGY FOR 28 YEARS OF HISTORICAL FLOWS FOR NWDT AWARD

Reservoir No.	Seasonal energy in 1000 kwhr						Remarks
	July to September			October to June			
	Req +	Actual	Shortage*	Req +	Actual	Shortage*	
1	2	3	4	5	6	7	8
1	11858	14938	1401	3953	7095	251	CHPH
2	316224	555671	4208	19764	33522	2274	RBPH
3	142301	261912	619	19764	32557	2205	RBPH
4	88279	160819	0	19764	25643	6343	RBPH
5	164700	173906	26136	19764	24502	6980	CHPH

	Reservoir 1		Reservoir 2		Reservoir 3		Reservoir 4		Reservoir 5	
	July to Sept	Oct to June	July to Sept	Oct to June	July to Sept	Oct to June	July to Sept	Oct to June	July to Sept	Oct to June
Power shortage index	4.833	3.00	0.302	10.80	0.053	8.080	0.000	18.40	4.63	16.18

* In calculating shortages, negative shortages are set to zero.

\+ Load factor = 60%.

TABLE 6.4.36. AVERAGE SEASONAL ENERGY FOR 50 YEARS OF SYNTHETIC FLOWS FOR NWDT AWARD

Reservoir No.	Seasonal energy in 1000 kwhr						Remarks
	July to September			October to June			
	Req +	Actual	Shortage*	Req +	Actual	Shortage*	
1	2	3	4	5	6	7	8
1	11858	14073	1675	3953	7231	173	CHPH
2	316224	527024	11772	19764	28196	5005	RBPH
3	142301	256044	2780	19764	28529	3830	RBPH
4	88279	156523	1177	19764	19225	9718	RBPH
5	164700	159975	33146	19764	24665	6895	CHPH

	Reservoir 1		Reservoir 2		Reservoir 3		Reservoir 4		Reservoir 5	
	July to Sept	Oct to June	July to Sept	Oct to June	July to Sept	Oct to June	July to Sept	Oct to June	July to Sept	Oct to June
Power shortage index	5.60	1.85	1.315	19.24	0.637	10.92	0.444	28.70	5.83	16.67

*In calculating shortages, negative shortages are set to zero.

+Load factor = 60%.

TABLE 6.4.37. AVERAGE SEASONAL ENERGY FOR 50 YEARS OF SYNTHETIC FLOWS FOR NWDT AWARD

Reservoir No.	Seasonal energy in 1000 kwhr						Remarks
	July to September			October to June			
	Req	Actual	Shortage*	Req+	Actual	Shortage*	
1	2	3	4	5	6	7	8
1	11858	15825	1087	3953	7130	229	CHPH
2	316224	546079	14867	19764	30050	4022	RBPH
3	142301	260890	1773	19764	30350	3266	RBPH
4	88279	160376	649	19764	22692	7902	RBPH
5	164700	175111	25468	19764	22813	7862	CHPH

	Reservoir 1		Reservoir 2		Reservoir 3		Reservoir 4		Reservoir 5	
	July to Sept	Oct to June	July to Sept	Oct to June	July to Sept	Oct to June	July to Sept	Oct to June	July to Sept	Oct to June
Power shortage index	3.66	2.43	1.375	13.22	0.390	7.58	0.225	21.66	4.27	20.00

* In calculating shortages, negative shortages are set to zero.

\+ Load factor = 60%.

TABLE 6.4.38. AVERAGE SEASONAL ENERGY FOR 50 YEARS OF SYNTHETIC FLOWS FOR NWDT AWARD

Reservoir No.	Seasonal energy in 1000 kwhr						Remarks
	July to September			October to June			
	Req +	Actual	Shortage*	Req +	Actual	Shortage*	
1	2	3	4	5	6	7	8
1	11858	15321	1365	3953	7121	227	
2	316224	546417	12877	19764	28466	4787	CHPH
3	142301	254100	5917	19764	32273	2614	RBPH
4	88279	155920	3042	19764	24805	6796	RBPH
5	164700	172768	27825	19764	25759	6324	RBPH
							CHPH

	Reservoir 1		Reservoir 2		Reservoir 3		Reservoir 4		Reservoir 5	
	July to Sept	Oct to June	July to Sept	Oct to June	July to Sept	Oct to June	July to Sept	Oct to June	July to Sept	Oct to June
Power shortage index	4.15	2.45	1.36	18.40	1.48	7.28	1.19	19.00	5.10	14.00

* In calculating shortages, negative shortages are set to zero.

\+ Load factor = 60%.

TABLE 6.4.39. AVERAGE SEASONAL ENERGY FOR FLOOD SIMULATION FOR 28 YEARS OF HISTORICAL FLOWS FOR NWDT AWARD

Reservoir No.	Seasonal energy in 1000 kwhr						Remarks
	July to September			October to June			
	Req +	Actual	Shortage*	Req +	Actual	Shortage*	
1	2	3	4	5	6	7	8
1	11858	15145	1477	3953	7095	251	CHPH
2	316224	531825	15267	19764	32018	3059	RBPH
3	142301	251157	4995	19764	32489	2443	RBPH
4	88279	155091	3055	19764	28056	5080	RBPH
5	164700	179766	24801	19764	29767	4235	CHPH

	Reservoir 1		Reservoir 2		Reservoir 3		Reservoir 4		Reservoir 5	
	July to Sept	Oct to June	July to Sept	Oct to June	July to Sept	Oct to June	July to Sept	Oct to June	July to Sept	Oct to June
Power shortage index	5.24	3.00	2.09	12.12	1.34	8.34	1.64	15.365	4.42	9.00

* In calculating shortages, negative shortages are set to zero.

\+ Load factor = 60%.

TABLE 6.4.40. AVERAGE SEASONAL ENERGY FOR FLOOD SIMULATION FOR 28 YEARS OF HISTORICAL FLOWS FOR MODIFIED NWDT AWARD

Reservoir No.	Seasonal energy in 1000 kwhr						Remarks
	July to September			October to June			
	Req +	Actual	Shortage*	Req +	Actual	Shortage*	
1	2	3	4	5	6	7	8
1	11858	15366	547	3953	7276	157	CHPH
2	316224	558577	10051	19764	32119	2980	RBPH
3	142301	261525	1694	19764	30139	3167	RBPH
4	88279	159035	1430	19764	25718	6340	RBPH
5	164700	170318	27465	19764	25104	6666	CHPH

	Reservoir 1		Reservoir 2		Reservoir 3		Reservoir 4		Reservoir 5	
	July to Sept	Oct to June	July to Sept	Oct to June	July to Sept	Oct to June	July to Sept	Oct to June	July to Sept	Oct to June
Power shortage index	0.63	2.20	0.94	12.96	0.40	13.10	0.44	21.84	3.28	17.00

* In calculating shortages, negative shortages are set to zero.

+ Load factor = 60%.

TABLE 6.4.41. RIGID RULES FOR DIFFERENT HYDROLOGICAL STATES OF BASIN FOR 28 YEARS OF HISTORICAL FLOWS FOR MODIFIED NWDT AWARD

Reservoir No.	Rule	End of month reservoir content (MAF)											
		July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	March	April	May	June
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Dry	1.785	3.503	3.945	3.763	3.244	2.777	2.423	2.149	1.988	1.760	1.536	1.397
	Ave	1.875	3.803	4.354	4.421	3.969	3.543	3.203	2.870	2.664	2.376	2.089	1.848
	Wet	1.875	3.826	4.984	4.987	4.346	3.832	3.497	3.172	2.968	2.650	2.352	2.121
	Very wet	1.867	4.326	5.942	5.467	4.609	4.109	3.691	3.370	3.169	2.790	2.483	2.187
2	Dry	3.004	6.065	4.165	3.171	2.726	2.329	2.173	2.095	1.731	1.697	1.384	1.211
	Ave	3.926	8.510	8.335	7.817	7.230	6.702	6.117	5.531	4.995	4.467	3.923	3.510
	Wet	3.600	6.982	9.121	9.177	8.569	7.853	7.268	6.669	6.080	5.504	4.875	4.271
	Very wet	5.225	10.300	14.364	12.740	10.884	9.535	8.817	8.098	7.387	6.671	5.951	5.250
3	Dry	0.576	0.868	0.883	0.818	0.697	0.600	0.563	0.560	0.560	0.560	0.550	0.541
	Ave	0.630	1.013	1.259	1.194	1.006	0.881	0.740	0.640	0.613	0.600	0.586	0.478
	Wet	0.660	0.927	1.344	1.290	1.113	0.994	0.854	0.768	0.696	0.680	0.640	0.581
	Very wet	0.752	1.170	1.600	1.422	1.250	1.158	1.001	0.913	0.826	0.760	0.693	0.640
4	Dry	0.289	0.385	0.154	0.181	0.175	0.247	0.228	0.266	0.248	0.219	0.184	0.165
	Ave	0.316	0.367	0.293	0.316	0.297	0.297	0.280	0.273	0.264	0.258	0.247	0.321
	Wet	0.367	0.385	0.368	0.358	0.366	0.362	0.349	0.336	0.326	0.322	0.329	0.344
	Very wet	0.375	0.385	0.400	0.381	0.377	0.371	0.364	0.356	0.352	0.350	0.349	0.375

Contd...

TABLE 6.4.41 (Contd.)

1	2	3	4	5	6	7	8	9	10	11	12	13	14
5	Dry	3.0[illegible]9	4.740	7.454	6.226	5.179	4.120	3.340	2.920	2.843	2.790	2.732	2.785
	Ave	3.039	4.739	7.672	6.841	5.838	4.870	3.991	3.137	2.953	2.910	2.862	2.903
	Wet	3.073	4.833	7.750	6.886	6.320	5.630	4.854	4.023	3.700	3.512	3.369	3.708
	Very wet	3.100	5.185	7.750	7.143	6.917	6.590	5.964	5.215	4.900	4.651	4.441	5.171

Reservoir No.	Maximum storage in MAF	Minimum storage in MAF
1	6.25	0.600
2	15.00	2.000
3	1.60	0.560
4	0.40	0.375
5	7.75	2.970

TABLE 6.4.42. RIGID RULES FOR DIFFERENT HYDROLOGICAL STATES OF BASIN FOR 50 YEARS OF SYNTHETIC FLOWS FOR MODIFIED NWDT AWARD

Reservoir No.	Rule	End of month reservoir content (MAF)											
		July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	March	April	May	June
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Dry	1.828	3.221	3.492	3.373	2.891	2.481	2.175	1.883	1.708	1.498	1.289	1.195
	Ave	1.689	4.022	4.515	4.532	4.074	3.661	3.322	2.986	2.768	2.492	2.201	1.958
	Wet	1.852	4.073	5.069	4.943	4.346	3.844	3.505	3.179	2.936	2.646	2.349	2.092
	Very wet	1.746	4.220	5.703	5.396	4.574	3.997	3.669	3.344	3.068	2.769	2.464	2.180
2	Dry	3.316	5.802	3.697	2.806	2.397	2.024	1.883	1.577	1.632	1.478	1.322	1.175
	Ave	3.766	7.404	6.189	5.542	4.905	4.408	3.887	3.387	2.973	2.600	2.227	2.194
	Wet	3.793	8.127	8.207	7.838	7.408	6.888	6.305	5.718	5.198	4.686	4.175	3.818
	Very wet	3.314	7.098	12.275	12.735	11.217	9.750	9.000	8.250	7.500	6.750	6.000	5.250
3	Dry	0.548	0.802	0.852	0.733	0.631	0.565	0.549	0.547	0.548	0.545	0.538	0.531
	Ave	0.622	0.928	1.100	1.026	0.826	0.684	0.596	0.564	0.560	0.558	0.554	0.491
	Wet	0.598	0.966	1.238	1.174	0.983	0.845	0.715	0.644	0.616	0.602	0.586	0.531
	Very wet	0.584	0.922	1.500	1.440	1.274	1.200	1.040	0.960	0.880	0.800	0.720	0.640
4	Dry	0.329	0.381	0.191	0.233	0.220	0.225	0.186	0.182	0.179	0.170	0.135	0.170
	Ave	0.314	0.365	0.229	0.299	0.319	0.310	0.285	0.285	0.284	0.264	0.238	0.257
	Wet	0.328	0.385	0.338	0.338	0.332	0.319	0.290	0.277	0.278	0.272	0.257	0.295
	Very wet	0.375	0.385	0.383	0.376	0.392	0.390	0.385	0.380	0.375	0.375	0.375	0.375

Contd...

TABLE 6.4.42 (Contd.)

1	2	3	4	5	6	7	8	9	10	11	12	13	14
5	Dry	3.061	4.534	7.302	6.303	5.248	4.155	3.334	2.925	2.866	2.812	2.755	2.960
	Ave	2.956	4.543	7.481	6.935	6.032	5.103	4.198	3.232	2.960	2.910	2.851	2.992
	Wet	3.002	5.059	7.706	6.861	5.964	5.019	4.172	3.378	3.101	3.015	2.948	3.278
	Very wet	3.039	5.173	7.750	7.188	6.786	6.554	5.946	5.178	4.836	4.467	4.249	4.726

Reservoir No.	Maximum storage in MAF	Minimum storage in MAF
1	6.25	0.600
2	15.00	2.000
3	1.60	0.560
4	0.40	0.375
5	7.75	2.970

TABLE 6.4.43. RIGID RULES FOR DIFFERENT HYDROLOGICAL STATES OF THE BASIN FOR 50 YEARS OF SYNTHETIC FLOWS FOR MODIFIED NWDT AWARD

Reservoir No.	Rule	End of month reservoir content. (MAF)											
		July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	March	April	May	June
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Dry	1.798	3.311	3.808	3.769	3.283	2.827	2.510	2.209	2.003	1.780	1.548	1.410
	Ave	1.875	4.095	4.724	4.536	4.056	3.611	3.260	2.922	2.703	2.432	2.146	1.912
	Wet	1.762	4.016	5.221	5.024	4.354	3.836	3.497	3.167	2.925	2.634	2.335	2.100
	Very wet	1.875	4.187	5.871	5.537	4.672	4.063	3.737	3.418	3.125	2.813	2.500	2.187
2	Dry	3.321	4.733	3.241	2.610	2.301	2.046	1.770	1.508	1.403	1.182	1.251	1.219
	Ave	3.943	7.876	6.674	5.694	5.020	4.500	3.970	3.464	3.025	2.632	2.242	2.380
	Wet	3.215	8.528	10.038	9.838	9.249	8.505	7.871	7.223	6.623	6.023	5.400	4.803
	Very wet	4.500	8.991	13.213	12.959	11.196	9.750	9.000	8.250	7.500	6.750	6.000	5.250
3	Dry	0.590	0.750	0.856	0.740	0.618	0.563	0.600	0.600	0.600	0.600	0.550	0.551
	Ave	0.627	0.977	1.150	1.053	0.859	0.722	0.615	0.571	0.562	0.559	0.555	0.498
	Wet	0.563	0.987	1.353	1.292	1.130	1.012	0.881	0.781	0.705	0.660	0.626	0.574
	Very wet	0.640	1.003	1.545	1.418	1.274	1.200	1.040	0.960	0.880	0.800	0.720	0.640
4	Dry	0.316	0.368	0.212	0.247	0.256	0.272	0.248	0.229	0.205	0.171	0.162	0.186
	Ave	0.326	0.385	0.292	0.265	0.274	0.292	0.299	0.267	0.262	0.249	0.226	0.238
	Wet	0.322	0.385	0.386	0.338	0.354	0.347	0.345	0.335	0.328	0.324	0.307	0.329
	Very wet	0.375	0.385	0.380	0.381	0.394	0.390	0.385	0.380	0.375	0.375	0.375	0.375

Contd...

TABLE 6.4.43 (Contd.)

1	2	3	4	5	6	7	8	9	10	11	12	13	14
5	Dry	3.015	4.353	7.305	6.534	5.532	4.392	3.468	3.005	2.896	2.849	2.795	2.807
	Ave	3.100	5.060	7.735	6.712	5.748	4.764	3.858	3.156	2.962	2.876	2.819	3.013
	Wet	3.009	5.354	7.750	6.857	6.200	5.503	4.684	3.852	3.552	3.340	3.213	3.504
	Very wet	3.084	5.188	7.750	7.263	7.063	6.834	6.205	5.413	5.087	4.687	4.380	4.722

Reservoir No.	Maximum storage in MAF	Minimum storage in MAF
1	6.25	0.600
2	15.00	2.000
3	1.60	0.560
4	0.40	0.375
5	7.75	2.970

TABLE 6.4.44. RIGID RULES FOR DIFFERENT HYDROLOGICAL STATES OF BASIN FOR 50 YEARS OF SYNTHETIC FLOWS FOR MODIFIED NWDT AWARD

Reservoir No.	Rule	End of month reservoir content (MAF)											
		July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	March	April	May	June
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Dry	1.667	3.363	3.554	3.422	2.927	2.506	2.162	1.854	1.683	1.474	1.280	1.194
	Ave	1.748	3.497	4.132	4.066	3.579	3.160	2.819	2.490	2.291	2.058	1.801	1.602
	Wet	1.771	4.116	5.219	5.116	4.477	3.945	3.612	3.285	3.031	2.737	2.433	2.158
	Very wet	1.875	4.033	5.550	5.272	4.495	3.921	3.590	3.268	3.000	2.698	2.393	2.214
2	Dry	2.791	5.908	3.644	2.711	2.989	1.981	1.666	1.534	1.370	1.110	0.992	1.013
	Ave	3.867	7.380	6.911	6.284	5.638	5.105	4.542	3.997	3.521	3.114	2.711	2.431
	Wet	4.158	8.921	9.685	9.756	9.307	8.561	7.894	7.218	6.569	5.926	5.263	4.467
	Very wet	3.774	8.322	13.631	13.278	11.211	9.750	9.000	8.250	7.500	6.750	6.000	5.250
3	Dry	0.560	0.881	0.898	0.775	0.651	0.580	0.560	0.560	0.560	0.558	0.547	0.541
	Ave	0.604	0.926	1.151	1.079	0.885	0.736	0.622	0.569	0.560	0.556	0.556	0.507
	Wet	0.629	1.025	1.343	1.292	1.110	1.041	0.894	0.812	0.759	0.710	0.662	0.597
	Very wet	0.620	0.975	1.582	1.491	1.275	1.200	1.040	0.960	0.880	0.800	0.720	0.640
4	Dry	0.277	0.362	0.167	0.236	0.244	0.249	0.234	0.188	0.166	0.158	0.149	0.129
	Ave	0.305	0.360	0.310	0.287	0.268	0.254	0.215	0.255	0.269	0.255	0.231	0.223
	Wet	0.353	0.385	0.360	0.359	0.363	0.362	0.354	0.324	0.319	0.318	0.310	0.341
	Very wet	0.312	0.377	0.402	0.400	0.395	0.390	0.385	0.380	0.375	0.375	0.375	0.375

Contd...

TABLE 6.4.44 (Contd.)

1	2	3	4	5	6	7	8	9	10	11	12	13	14
5	Dry	2.932	4.502	7.398	6.207	5.148	4.082	3.260	2.980	2.859	2.810	2.753	2.763
	Ave	3.066	5.000	7.727	6.727	5.708	4.732	3.846	3.039	2.924	2.871	2.816	2.864
	Wet	3.072	5.000	7.677	7.014	6.286	5.578	4.870	4.096	3.771	3.492	3.370	3.689
	Very wet	2.997	5.033	7.944	7.306	7.130	6.934	6.407	5.678	5.368	5.009	4.719	5.190

Reservoir No.	Maximum storage in MAF	Minimum storage in MAF
1	6.25	0.600
2	15.00	2.000
3	1.60	0.560
4	0.40	0.375
5	7.75	2.970

TABLE 6.4.45. RIGID RULES FOR DIFFERENT HYDROLOGICAL STATES OF BASIN FOR 28 YEARS OF HISTORICA FLOWS FOR NWDT AWARD

Rese-rvoir No.	Rule	End of month reservoir content (MAF)											
		July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	March	April	May	June
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Dry	1.635	3.494	4.113	4.086	3.682	3.332	3.094	2.865	2.715	2.466	2.245	2.00
	Ave	1.723	3.704	4.155	4.242	3.795	3.403	3.059	2.722	2.516	2.243	1.965	1.79
	Wet	1.630	3.484	4.381	4.390	3.656	2.994	2.468	2.038	1.810	1.528	1.228	1.064
	Very wet	1.641	4.129	5.424	5.082	4.141	3.312	2.613	1.942	1.624	1.228	0.874	0.81
2	Dry	3.342	6.564	4.498	3.659	3.433	3.189	2.843	2.513	2.458	2.475	2.150	2.086
	Ave	3.830	8.410	8.810	7.606	7.105	6.588	6.020	5.472	4.960	4.455	3.925	3.484
	Wet	3.644	7.042	8.925	8.986	8.268	7.488	6.845	6.189	5.559	4.960	4.347	3.833
	Very wet	4.926	9.746	13.656	12.326	10.720	9.362	8.621	7.888	7.143	6.400	5.655	5.084
3	Dry	0.479	0.818	0.887	0.858	0.814	0.776	0.736	0.691	0.635	0.580	0.543	0.517
	Ave	0.598	1.014	1.282	1.240	1.091	0.974	0.860	0.751	0.680	0.617	0.569	0.470
	Wet	0.592	0.858	1.236	1.203	0.997	0.857	0.730	0.656	0.628	0.594	0.557	0.516
	Very wet	0.698	1.137	1.560	1.341	1.127	1.093	0.944	0.856	0.792	0.722	0.602	0.615
4	Dry	0.342	0.384	0.237	0.284	0.295	0.251	0.274	0.301	0.308	0.293	0.309	0.309
	Ave	0.361	0.385	0.287	0.276	0.301	0.279	0.253	0.262	0.296	0.313	0.283	0.300
	Wet	0.359	0.385	0.354	0.315	0.371	0.372	0.350	0.304	0.313	0.307	0.289	0.307
	Very wet	0.361	0.385	0.400	0.347	0.390	0.385	0.353	0.360	0.359	0.354	0.352	0.356

Contd...

TABLE 6.4.45 (Contd.)

1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Dry	3.095	5.149	7.711	7.033	6.317	5.661	4.998	4.301	3.861	3.511	3.314	3.270
5	Ave	3.037	4.783	7.647	6.898	5.921	4.971	4.097	3.267	2.970	2.944	2.931	2.945
	Wet	2.976	4.650	7.651	6.490	5.656	4.646	3.720	3.120	2.935	2.878	2.835	3.000
	Very wet	3.051	5.059	7.750	6.611	6.181	5.345	4.413	3.535	3.135	2.981	2.933	3.317

Note: The award does not classify the basin into four categories as specified. It simply gives wet, average and dry. However four classifications, very wet, wet, average and dry are used for comparison with first four simulations.

TABLE 6.4.46. RIGID RULES FOR DIFFERENT HYDROLOGICAL STATES OF BASIN FOR 50 YEARS OF SYNTHETIC FLOWS FOR NWDT AWARD

Reservoir No.	Rule	End of month reservoir content (MAF)											
		July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	March	April	May	June
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Dry	1.741	3.271	3.798	3.810	3.478	3.154	2.930	2.700	2.520	2.300	2.071	1.915
	Ave	1.875	4.166	4.678	4.723	4.267	3.813	3.482	3.151	2.905	2.612	2.309	2.306
	Wet	1.678	3.855	4.675	4.500	3.763	3.152	2.653	2.178	1.908	1.593	1.270	1.116
	Very wet	1.847	4.131	5.253	5.256	4.312	3.487	2.801	2.137	1.769	1.400	1.021	0.736
2	Dry	3.141	5.768	3.850	3.087	2.850	2.624	2.332	2.157	1.906	1.790	1.543	1.476
	Ave	3.946	7.662	6.366	5.755	5.221	4.782	4.276	3.770	3.352	2.958	2.543	2.484
	Wet	3.745	7.935	7.829	7.205	6.608	5.988	5.360	4.755	4.183	3.684	3.203	2.890
	Very wet	3.333	6.841	11.893	12.104	10.874	9.735	8.986	8.246	7.500	6.750	5.997	5.250
3	Dry	0.564	0.828	0.966	0.927	0.850	0.773	0.691	0.637	0.594	0.559	0.533	0.517
	Ave	0.615	0.930	1.114	1.053	0.883	0.731	0.625	0.581	0.560	0.559	0.557	0.475
	Wet	0.574	0.924	1.161	1.060	0.803	0.656	0.585	0.560	0.562	0.559	0.549	0.469
	Very wet	0.474	0.748	1.320	1.234	1.017	0.960	0.854	0.779	0.718	0.670	0.553	0.543
4	Dry	0.355	0.382	0.267	0.291	0.265	0.252	0.250	0.257	0.251	0.258	0.258	0.258
	Ave	0.333	0.377	0.254	0.291	0.312	0.323	0.268	0.278	0.276	0.273	0.262	0.287
	Wet	0.331	0.385	0.306	0.334	0.361	0.329	0.315	0.276	0.269	0.241	0.211	0.263
	Very wet	0.292	0.385	0.336	0.354	0.395	0.373	0.330	0.344	0.339	0.332	0.366	0.360

Contd...

TABLE 6.4.46 (Contd.)

1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Dry	3.087	4.746	7.580	7.031	6.320	5.610	4.940	4.205	3.788	3.405	3.197	3.387
	Ave	2.998	4.569	7.535	7.096	6.263	5.370	4.545	3.612	3.195	3.008	2.880	3.010
5	Wet	2.964	4.904	7.682	6.564	5.419	4.222	3.249	2.924	2.837	2.782	2.724	3.007
	Very wet	2.848	4.698	7.635	6.935	6.112	5.073	4.171	3.467	3.015	2.910	2.893	3.185

Note: The award does not classify the basin into four categories as specified. It simply gives wet, average and dry. However, the four classifications, very wet, wet, average and dry are used for comparison with first four simulations.

Reservoir No.	Maximum storage in MAF	Minimum storage in MAF
1	6.25	0.600
2	15.00	2.000
3	1.60	0.560
4	0.40	0.375
5	7.75	2.970

TABLE 6.4.47. RIGID RULES FOR DIFFERENT HYDROLOGICAL STATES OF BASIN FOR 50 YEARS OF SYNTHETIC FLOWS FOR NWDT AWARD

Reservoir No.	Rule	End of month reservoir content (MAF)											
		July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	March	April	May	June
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Dry	1.626	3.282	4.001	4.087	3.747	3.423	3.197	2.957	2.770	2.546	2.303	2.103
	Ave	1.830	4.059	4.680	4.501	3.967	3.508	3.148	2.793	2.565	2.289	1.998	1.790
	Wet	1.773	3.944	4.922	4.656	3.824	3.120	2.531	2.000	1.716	1.406	1.117	0.964
	Very wet	1.549	3.835	5.213	5.000	4.054	3.232	2.537	1.927	1.619	1.265	0.918	0.675
2	Dry	3.544	5.029	3.639	3.109	2.948	2.725	2.421	2.162	1.912	1.679	1.446	1.495
	Ave	3.736	7.676	6.370	5.415	4.865	4.353	3.815	3.297	2.861	2.490	2.113	2.110
	Wet	3.254	8.417	9.653	9.105	8.470	7.784	7.118	6.460	5.820	5.200	4.567	4.036
	Very wet	4.306	8.596	12.813	12.364	10.940	9.689	8.946	8.198	7.458	6.709	5.957	5.233
3	Dry	0.614	0.845	1.025	0.999	0.914	0.831	0.748	0.670	0.632	0.600	0.565	0.552
	Ave	0.610	0.967	1.151	1.067	0.885	0.762	0.669	0.609	0.585	0.566	0.555	0.532
	Wet	0.513	0.912	1.230	1.126	0.869	0.725	0.604	0.580	0.570	0.558	0.490	0.502
	Very wet	0.612	0.939	1.451	1.328	1.123	1.029	0.890	0.776	0.686	0.629	0.506	0.526
4	Dry	0.338	0.367	0.310	0.310	0.242	0.241	0.276	0.248	0.264	0.264	0.243	0.247
	Ave	0.354	0.385	0.287	0.284	0.290	0.290	0.250	0.249	0.251	0.239	0.213	0.242
	Wet	0.317	0.385	0.369	0.287	0.347	0.352	0.336	0.274	0.260	0.248	0.244	0.288
	Very wet	0.341	0.371	0.357	0.373	0.395	0.390	0.368	0.370	0.352	0.347	0.360	0.356

Contd...

TABLE 6.4.47 (Contd.)

1	2	3	4	5	6	7	8	9	10	11	12	13	14
5	Dry	3.052	4.591	7.582	7.130	6.504	5.785	5.072	4.355	3.880	3.561	3.378	3.312
	Ave	3.043	5.003	7.704	6.682	5.775	4.808	3.941	3.263	3.002	2.885	2.835	3.013
	Wet	2.993	5.320	7.750	6.514	5.293	4.030	3.193	2.981	2.898	2.845	2.820	2.886
	Very wet	3.043	5.047	7.746	7.030	6.380	5.467	4.388	3.424	3.001	2.930	2.921	3.096

Note: The award does not classify the basin into four categories as specified. It simply gives wet, average, and dry. However, the four classifications, very wet, wet, average, and dry are used for comparison with first four simulations.

Reservoir No.	Maximum storage in MAF	Minimum storage in MAF
1	6.25	0.600
2	15.00	2.000
3	1.60	0.560
4	0.40	0.375
5	7.75	2.970

TABLE 6.4.48. RIGID RULES FOR DIFFERENT HYDROLOGICAL STATES OF BASIN FOR 50 YEARS OF SYNTHETIC FLOWS FOR NWDT AWARD

Rese-rvoir No.	Rule	End of month reservoir content (MAF)											
		July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	March	April	May	June
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Dry	1.646	3.401	3.865	3.886	3.624	3.371	3.160	2.933	2.732	2.497	2.252	2.057
	Ave	1.670	3.444	4.135	4.127	3.730	3.348	3.037	2.734	2.517	2.275	2.202	1.816
	Wet	1.585	3.937	4.854	4.732	3.960	3.310	2.765	2.245	1.967	1.629	1.290	1.181
	Very wet	1.861	3.926	5.164	4.955	4.010	3.202	2.517	1.947	1.628	1.282	0.936	0.787
2	Dry	3.175	6.528	4.173	3.364	3.032	2.704	2.384	2.103	1.852	1.637	1.406	1.264
	Ave	3.553	7.150	6.608	6.052	5.514	5.026	4.495	3.977	3.572	3.179	2.750	2.413
	Wet	4.086	8.627	9.132	8.859	8.276	7.560	6.915	6.276	5.667	5.083	4.490	4.051
	Very wet	3.527	7.886	13.212	12.778	11.101	9.707	8.966	8.214	7.471	6.724	5.974	5.241
3	Dry	0.588	0.936	0.997	0.980	0.938	0.895	0.815	0.723	0.665	0.607	0.565	0.540
	Ave	0.569	0.926	1.187	1.153	1.026	0.927	0.830	0.738	0.673	0.623	0.580	0.507
	Wet	0.607	0.979	1.260	1.182	0.950	0.807	0.689	0.628	0.596	0.585	0.525	0.529
	Very wet	0.590	0.922	1.500	1.380	1.180	1.148	0.988	0.877	0.782	0.731	0.611	0.590
4	Dry	0.350	0.384	0.233	0.288	0.266	0.244	0.304	0.292	0.308	0.293	0.304	0.295
	Ave	0.328	0.385	0.323	0.313	0.275	0.272	0.238	0.267	0.285	0.255	0.276	0.261
	Wet	0.360	0.383	0.334	0.315	0.367	0.360	0.340	0.266	0.263	0.250	0.244	0.266
	Very wet	0.333	0.383	0.395	0.391	0.395	0.390	0.374	0.376	0.370	0.359	0.356	0.355

Contd...

TABLE 6.4.48 (Contd.)

1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Dry	3.084	4.887	7.750	7.065	6.389	5.726	5.043	4.400	3.958	3.593	3.341	3.220
5	Ave	3.026	5.084	7.748	6.884	6.008	5.106	4.312	3.425	3.095	2.957	2.905	2.947
	Wet	3.012	4.802	7.646	6.763	5.710	4.579	3.583	3.093	2.967	2.887	2.859	2.944
	Very wet	2.987	4.785	7.943	7.178	6.670	5.895	4.709	3.707	3.172	2.942	2.958	3.250

Note: The award does not classify the basin into four categories as specified. It simply gives wet, average, and dry. However, the four classifications, very wet, wet, average and dry are used for comparison with first four simulations.

Reservoir No.	Maximum storage in MAF	Minimum storage in MAF
1	6.25	0.600
2	15.00	2.000
3	1.60	0.560
4	0.40	0.375
5	7.75	2.970

TABLE 6.4.49. RIGID RULES FOR DIFFERENT HYDROLOGICAL STATES OF BASIN FOR FLOOD SIMULATION FOR 28 YEARS OF HISTORICAL FLOWS FOR NWDT AWARD

Reservoir No.	Rule	End of month reservoir content (MAF)											
		July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	March	April	May	June
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Dry	2.096	3.548	3.510	3.715	3.266	3.337	2.694	3.168	3.391	2.972	3.000	2.330
	Ave	2.388	4.155	3.887	4.106	3.276	4.422	2.753	3.090	3.300	3.110	2.966	2.745
	Wet	2.024	3.657	4.380	4.377	3.655	2.995	2.468	2.038	1.810	1.528	1.228	1.064
	Very wet	2.323	4.133	4.990	4.627	4.178	3.670	2.498	2.551	2.892	2.225	1.940	1.113
2	Dry	4.364	6.378	5.553	4.111	1.971	3.738	2.180	3.027	4.050	2.625	2.786	3.548
	Ave	5.614	9.298	11.076	8.827	7.468	8.677	6.245	6.968	7.375	6.164	4.554	5.743
	Wet	4.436	7.090	8.743	8.384	8.694	7.678	7.000	6.329	5.676	5.053	4.420	3.878
	Very wet	6.745	9.201	14.372	11.703	8.941	9.070	6.537	7.587	7.870	5.626	6.235	4.786
3	Dry	0.624	0.893	0.895	0.826	0.602	0.845	0.558	0.755	0.726	0.622	0.656	0.614
	Ave	0.757	1.156	1.407	1.308	1.052	1.190	0.862	0.935	0.891	0.848	0.774	0.700
	Wet	0.673	0.905	1.243	1.150	1.061	0.955	0.819	0.725	0.689	0.637	0.568	0.558
	Very wet	0.773	1.129	1.520	1.346	1.144	1.269	0.741	0.910	0.922	0.844	0.861	0.583
4	Dry	0.362	0.374	0.286	0.324	0.288	0.288	0.308	0.309	0.321	0.286	0.299	0.296
	Ave	0.368	0.340	0.345	0.358	0.348	0.360	0.353	0.337	0.355	0.315	0.303	0.363
	Wet	0.371	0.379	0.343	0.322	0.377	0.374	0.350	0.333	0.337	0.337	0.324	0.319
	Very wet	0.378	0.371	0.397	0.394	0.379	0.366	0.347	0.377	0.366	0.365	0.373	0.376

Contd...

TABLE 6.4.49 (Contd.)

1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Dry	3.608	5.296	7.032	6.510	6.267	5.805	4.763	5.289	4.760	4.700	4.641	4.068
5	Ave	3.816	5.894	7.126	6.893	6.385	5.621	4.201	4.323	4.222	4.117	4.257	3.930
	Wet	3.306	4.724	7.394	6.790	6.020	5.214	4.321	3.510	3.108	2.950	2.881	3.012
	Very wet	3.810	5.732	7.598	7.018	7.115	6.617	5.392	4.851	4.510	3.935	4.236	3.793

Note: The award does not classify the basin into four categories as specified. It simply gives wet, average, and dry. However, four classifications, very wet, wet, average, and dry are used for comparison with modified NWDT award for flood simulation run.

Reservoir No.	Maximum storage in MAF	Minimum storage in MAF
1	6.25	0.600
2	15.00	2.000
3	1.60	0.560
4	0.40	0.375
5	7.75	2.970

TABLE 6.4.50. RIGID RULES FOR DIFFERENT HYDROLOGICAL STATES OF BASIN FOR FLOOD SIMULATION FOR 28 YEARS OF HISTORICAL FLOWS FOR MODIFIED NWDT AWARD

Reservoir No.	Rule	End of month reservoir content (MAF)											
		July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	March	April	May	June
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Dry	1.784	3.503	3.945	3.763	3.244	2.778	2.428	2.148	1.988	1.760	1.535	1.397
	Ave	1.875	3.803	4.354	4.442	3.969	3.543	3.203	2.870	2.664	2.375	2.089	1.848
	Wet	1.875	3.827	4.984	4.987	4.346	3.832	3.497	3.172	2.968	2.650	2.352	2.121
	Very wet	1.867	4.326	5.942	5.467	4.610	4.019	3.692	3.370	3.170	2.790	2.483	2.188
2	Dry	3.369	6.566	4.630	3.634	3.185	2.775	2.578	2.496	2.126	2.060	1.711	1.516
	Ave	3.924	8.528	8.938	8.415	7.823	7.275	6.681	6.057	5.473	4.903	4.320	3.860
	Wet	3.869	7.230	10.491	9.965	9.056	8.283	7.694	7.071	6.466	5.859	5.187	4.539
	Very wet	5.088	10.325	14.491	12.860	10.888	9.540	8.820	8.102	7.390	6.674	5.954	5.250
3	Dry	0.595	0.901	0.920	0.855	0.734	0.639	0.574	0.559	0.559	0.557	0.551	0.529
	Ave	0.632	1.014	1.321	1.243	1.054	0.928	0.791	0.707	0.666	0.640	0.613	0.510
	Wet	0.629	0.894	1.425	1.314	1.138	1.016	0.877	0.801	0.737	0.711	0.666	0.606
	Very wet	0.759	1.206	1.600	1.430	1.252	1.160	1.000	0.914	0.828	0.760	0.693	0.640
4	Dry	0.300	0.385	0.149	0.175	0.170	0.250	0.207	0.287	0.269	0.243	0.212	0.192
	Ave	0.317	0.368	0.294	0.329	0.310	0.293	0.298	0.288	0.284	0.274	0.274	0.325
	Wet	0.365	0.385	0.369	0.377	0.378	0.373	0.360	0.347	0.344	0.344	0.339	0.347
	Very wet	0.375	0.385	0.405	0.380	0.377	0.371	0.364	0.356	0.352	0.352	0.350	0.375

Contd...

TABLE 6.4.50 (Contd.)

1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Dry	2.970	4.728	7.418	6.190	5.144	4.085	3.381	2.920	2.843	2.790	2.732	2.804
5	Ave	3.039	4.741	7.535	6.705	5.702	4.753	3.875	3.186	2.990	2.935	2.896	2.928
	Wet	3.068	4.833	7.750	6.982	6.393	5.738	4.956	4.124	3.790	3.607	3.478	3.812
	Very wet	3.100	5.116	7.750	7.236	6.917	6.589	5.964	5.215	4.900	4.650	4.400	5.175

Note: The award does not classify the basin into four categories as specified. It simply gives wet, average, and dry. However, four classifications, very wet, wet, average, and dry are used for comparison with modified NWDT award for flood simulation run.

Reservoir No.	Maximum storage in MAF	Minimum storage in MAF
1	6.25	0.600
2	15.00	2.000
3	1.60	0.560
4	0.40	0.375
5	7.75	2.970

of month storage versus period (month) for a few selected cases are shown in Figures 6.4.1 to 6.4.16. The storages at the end of June generally give a picture of carry over storag

6.4.6. Spills

The statistics of monthly spills from the terminal reservoir, namely Sardar Sarovar are tabulated in Tables 6.4. to 6.4.58 for each simulation run. It is found that there is spill during the July month because of the restriction impose on the level of storage (40% storage) by the end of July. If this limit is increased, the spill will be shifted to other months say August, September, and October. There is a possibility of spilling during the month of November in very wet years.

6.4.7. Flood simulation study

3-hourly maximum spill from the terminal reservoir, Sardar Sarovar is the output of flood simulation study. Two simulation runs are taken and the observed maximum spills are shown in Tables 6.4.59, and 6.4.60. In the flood simulation studies reported here, the lag method of flood routing is used for channel routing. In this method the ordinates of flood hydrographs are lagged by the time of travel between the two reservoirs. The time of travel from one reservoir to another has been given in Chapter 3 (Section 3.4).

From Tables 6.4.59, and 6.4.60, it is seen that there is more attenuation of flood in the case of NWDT than in the case of modified NWDT.

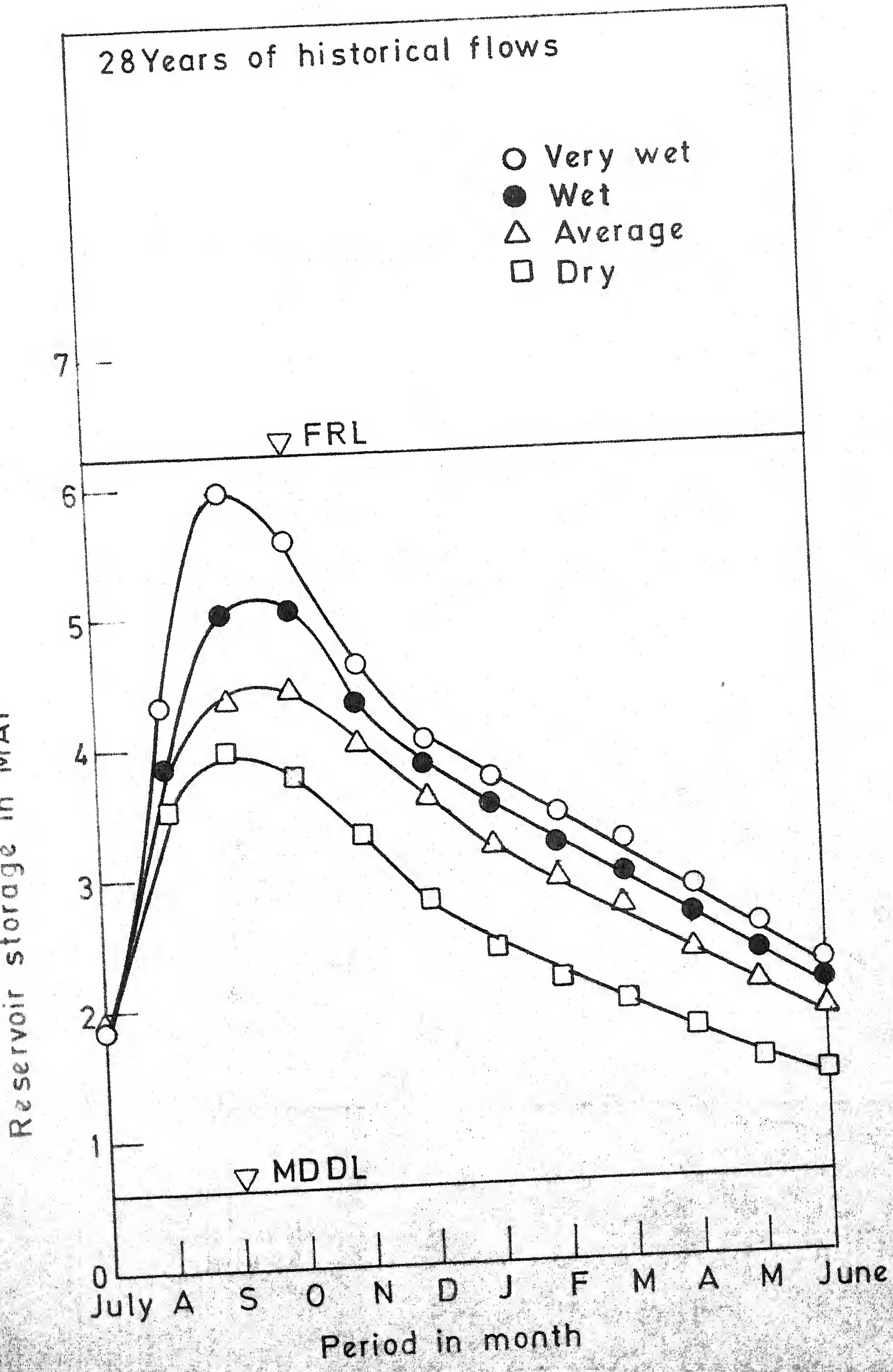


FIG 6.4.1 RIGID RULES FOR BARGI FOR MODIFIED NWDT AWARD

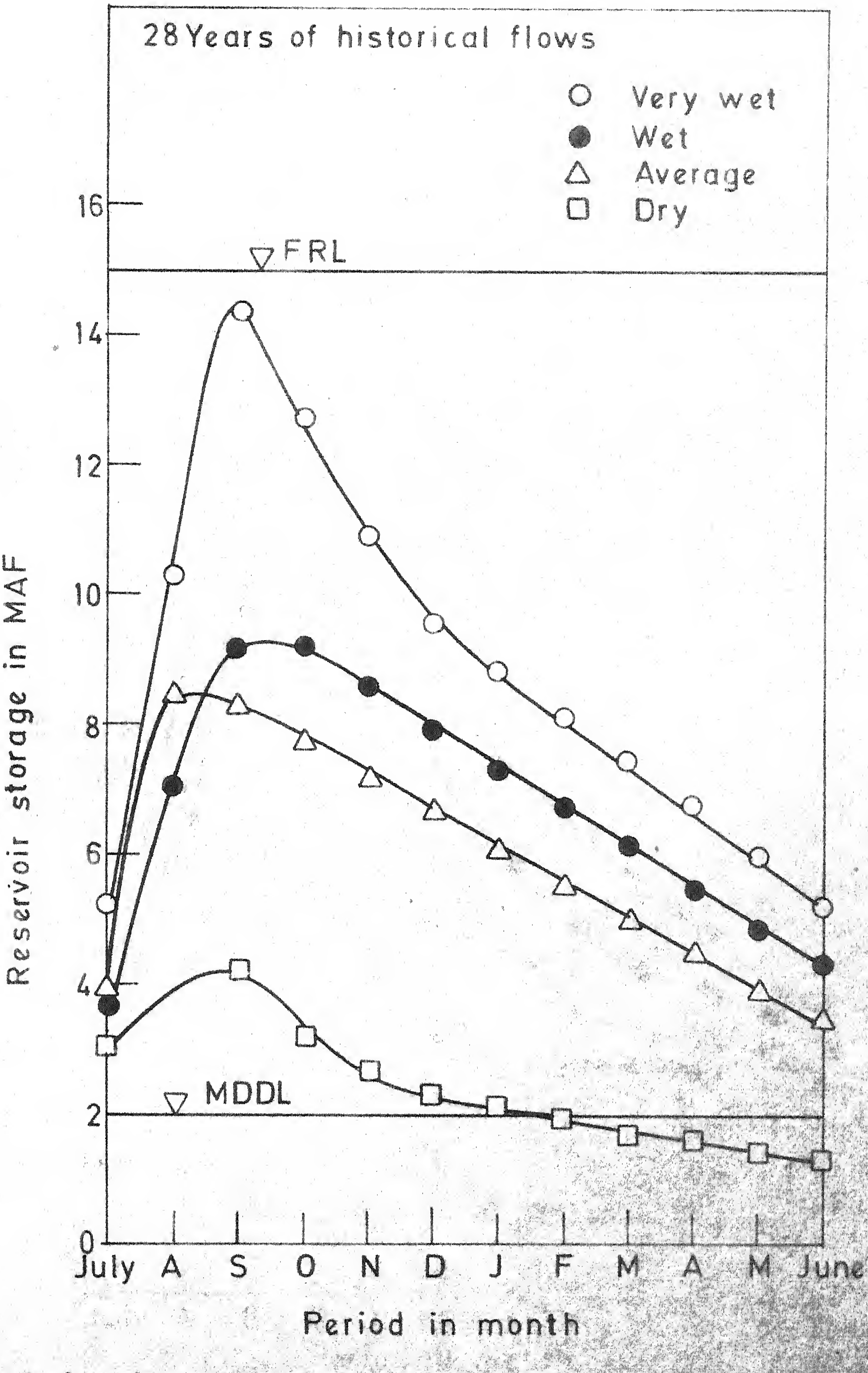


FIG. 6.4.2 RIGID RULE FOR NARMADASAGAR FOR MODIFIED NWDT AWARD

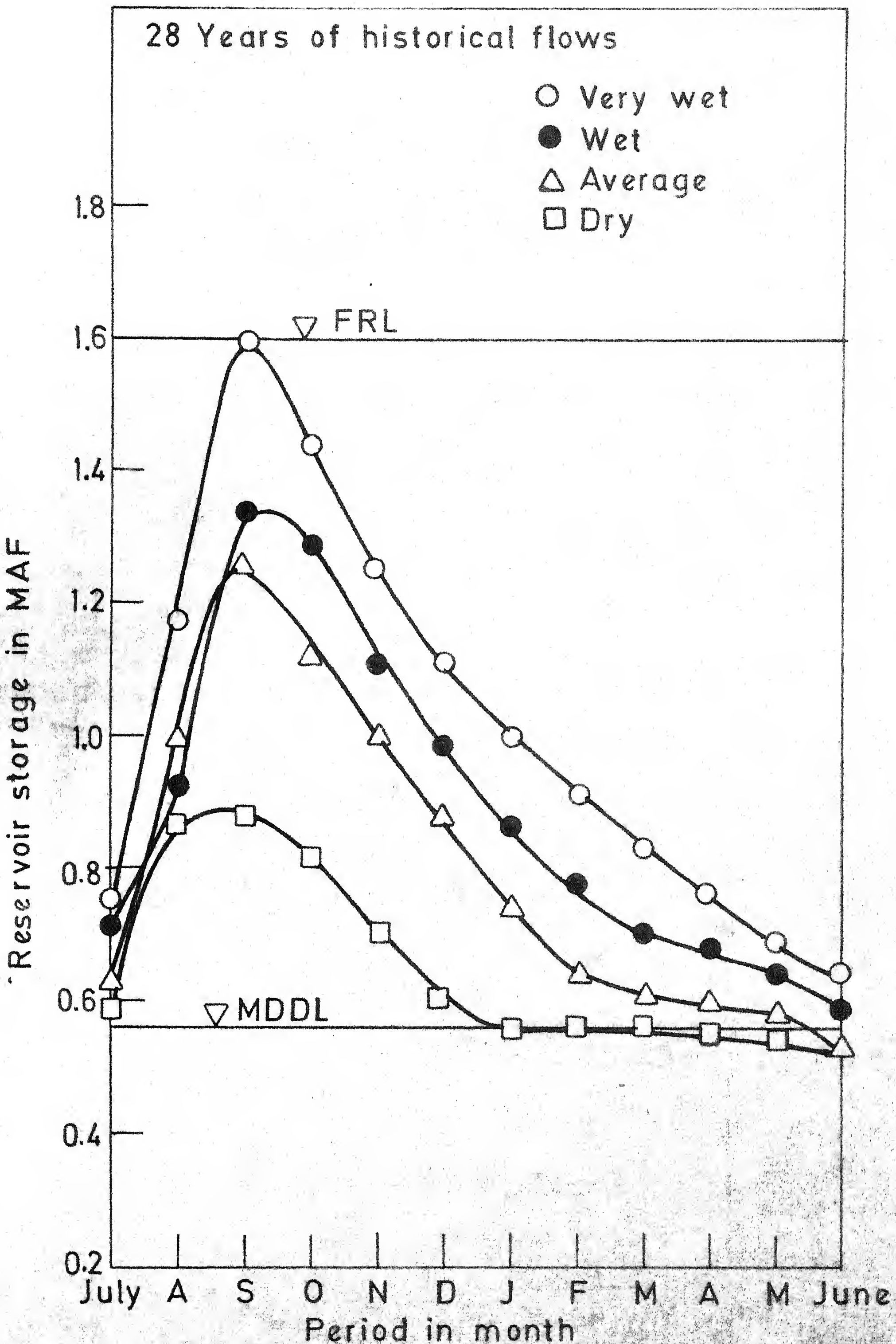


FIG. 6.4.3 RIGID RULES FOR OMKARESHWAR FOR

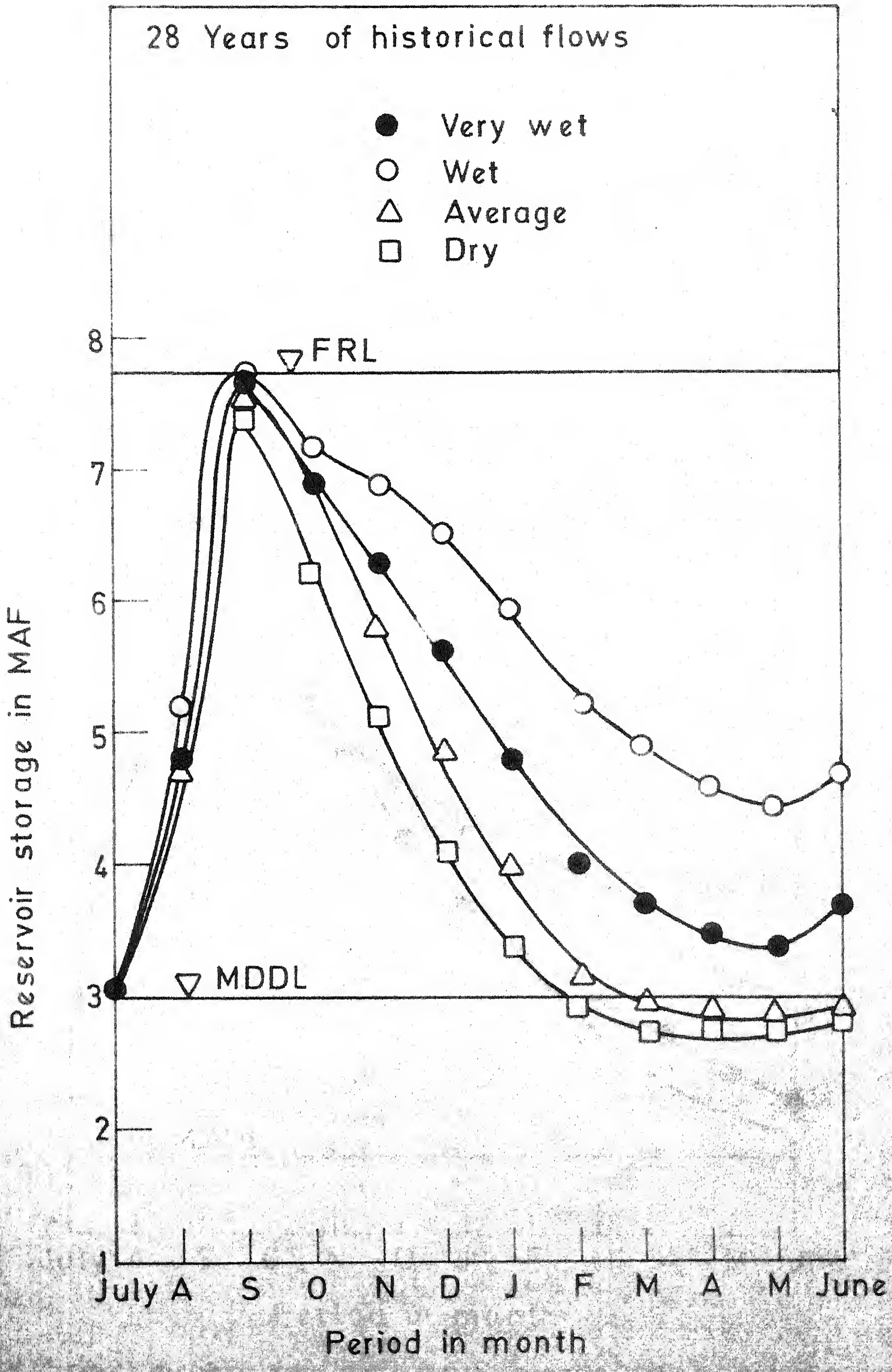


FIG. 6.4.4 RIGID RULES FOR SARDAR SAROVAR FOR MODIFIED NWDT AWARD

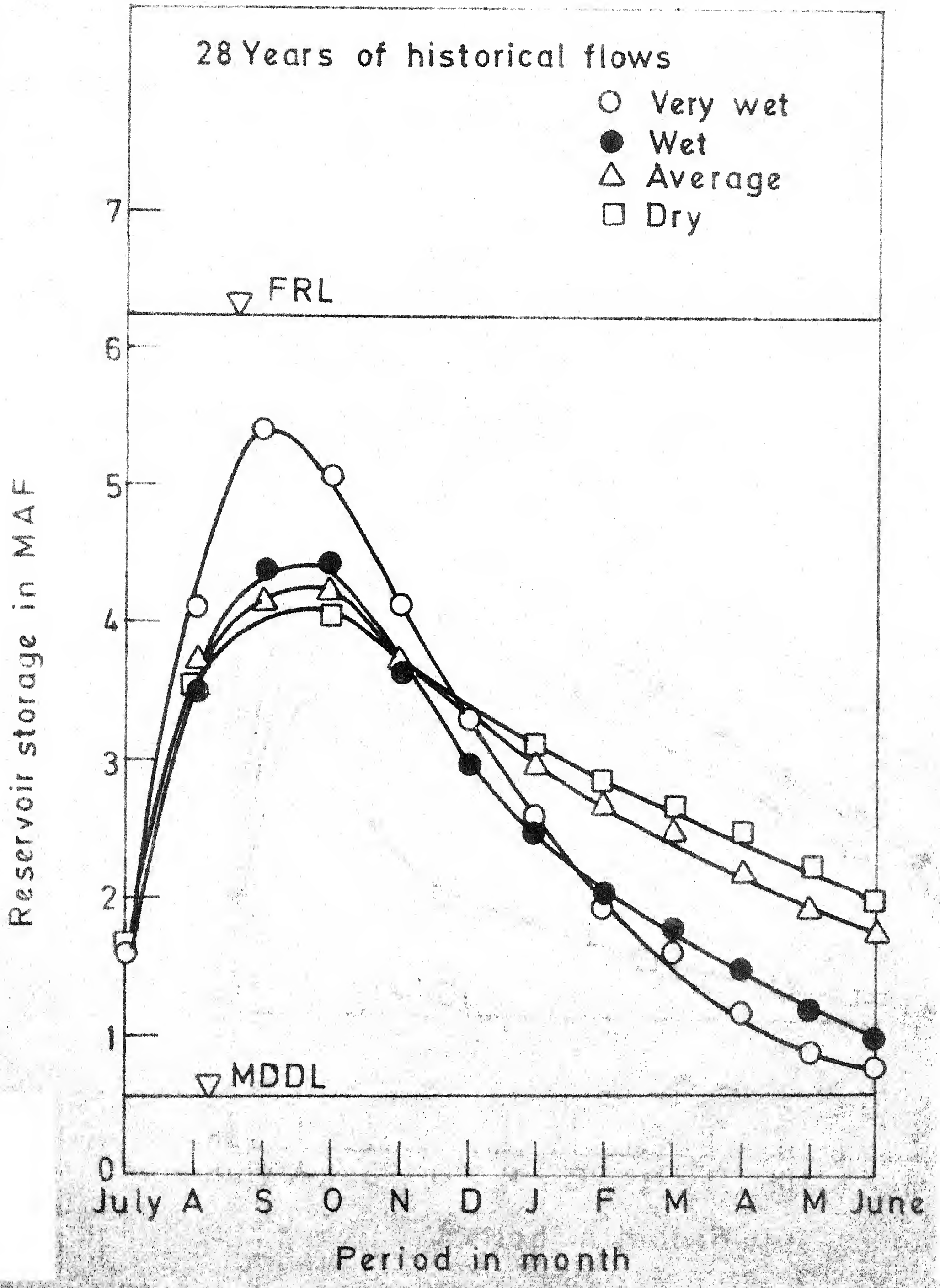


FIG 6.4.5 RIGID RULES FOR BARGI FOR NWDT AWARD

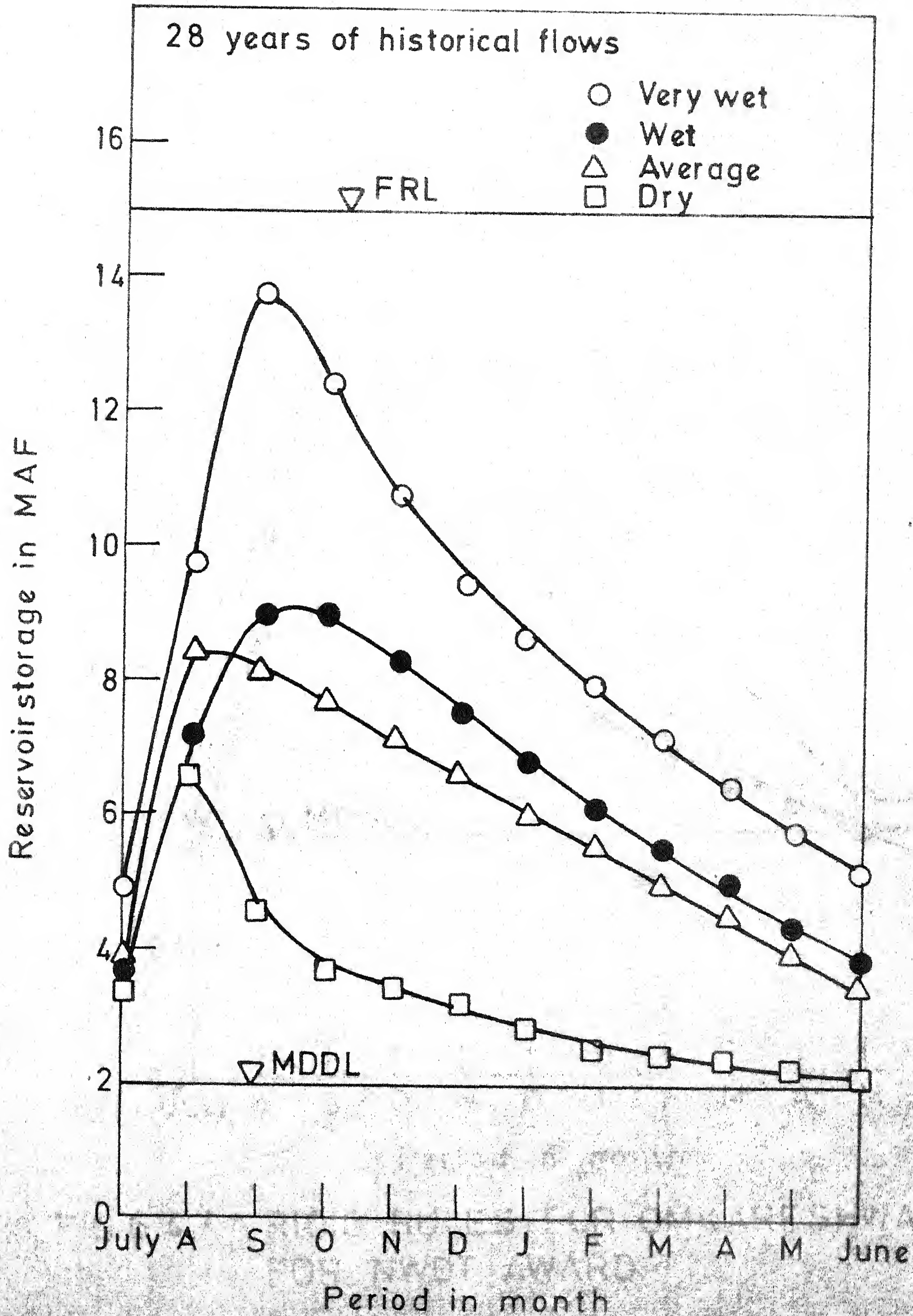


FIG. 6.4.6 RIGID RULES FOR NARMADASAGAR FOR NWDT AWARD

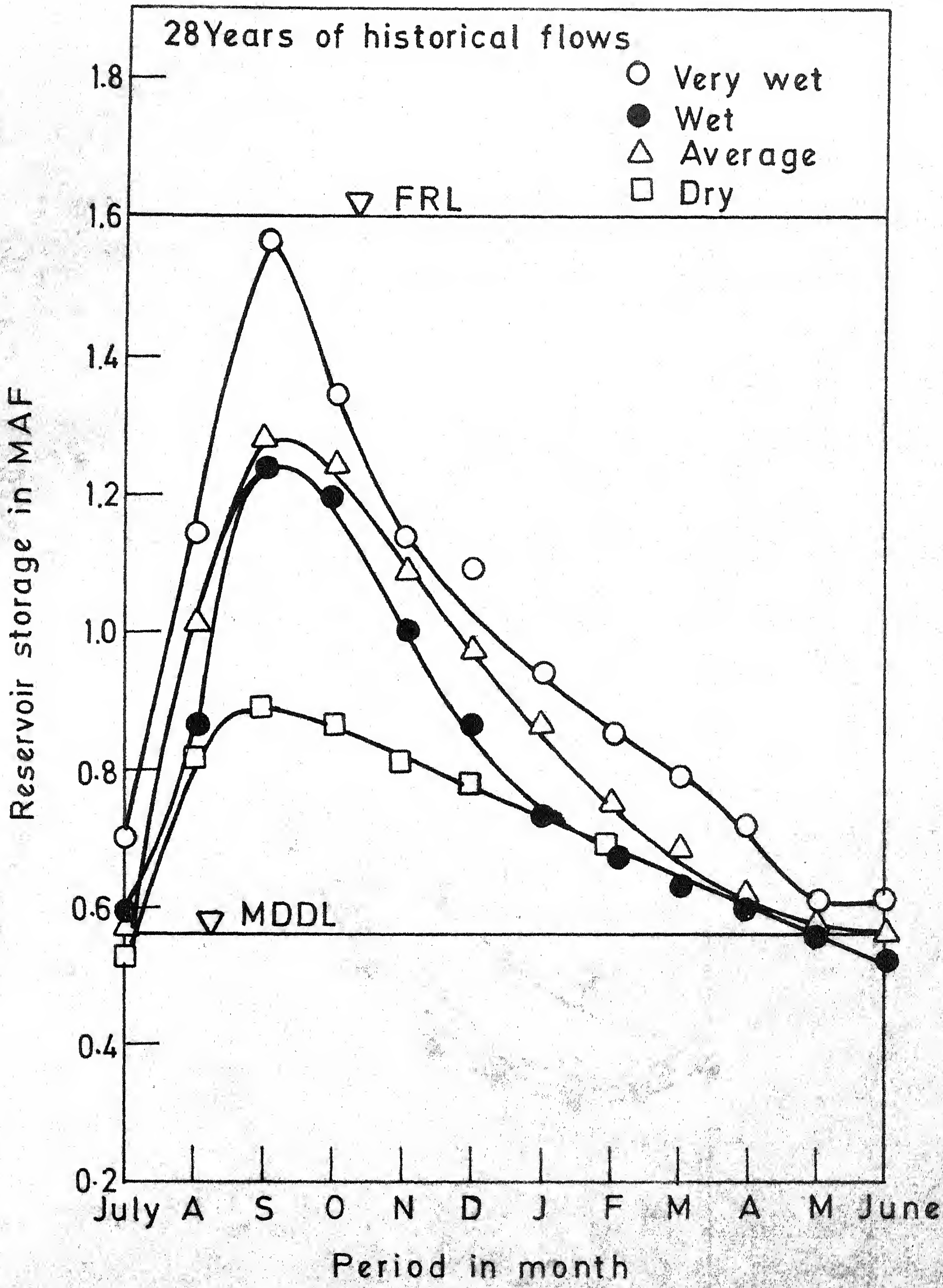


FIG. 6.4.7 RIGID RULES FOR OMKARESHWAR FOR NWDT AWARD

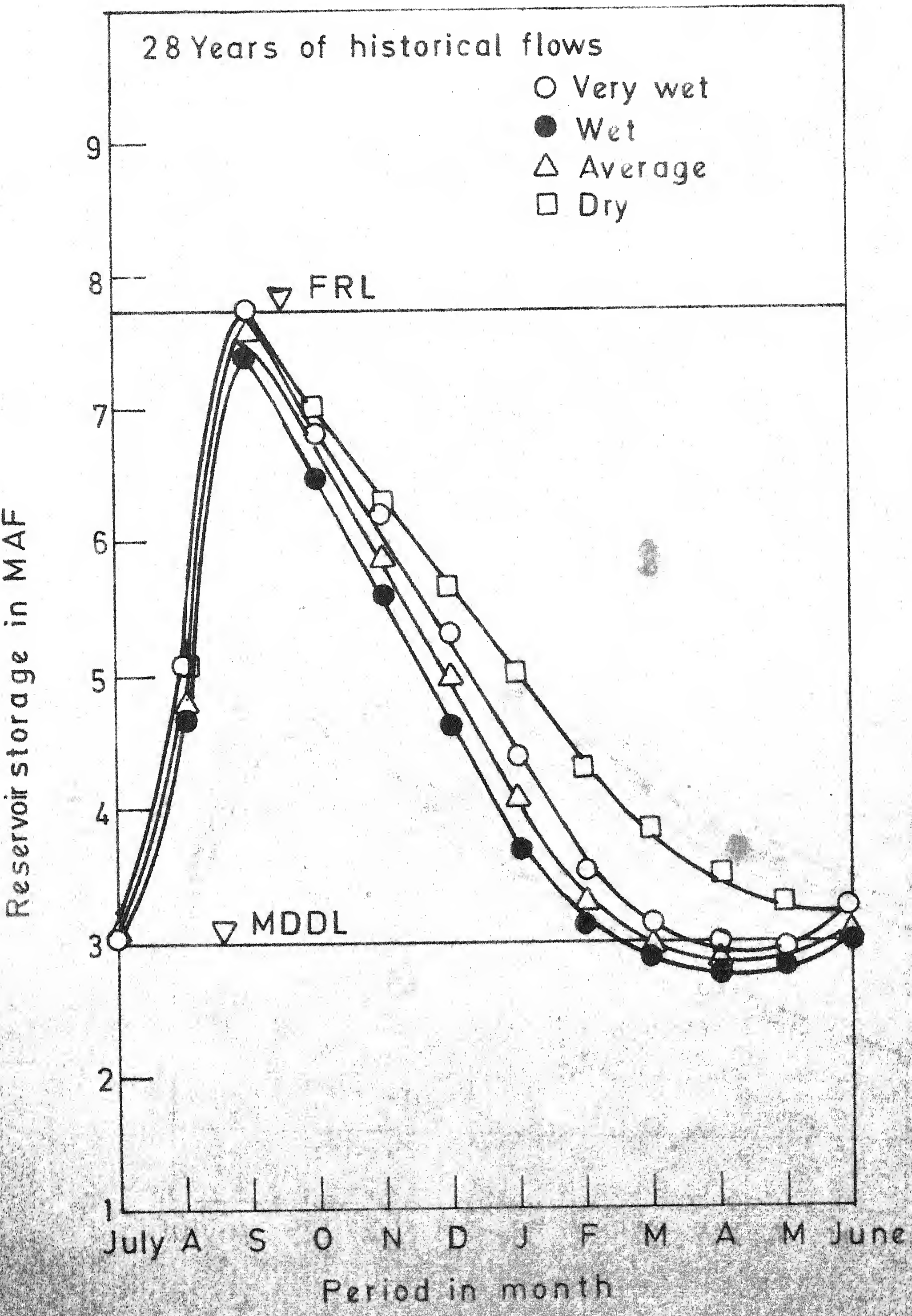


FIG. 6.4.8 RIGID RULES FOR SARDAR SAROVAR FOR NWDT AWARD

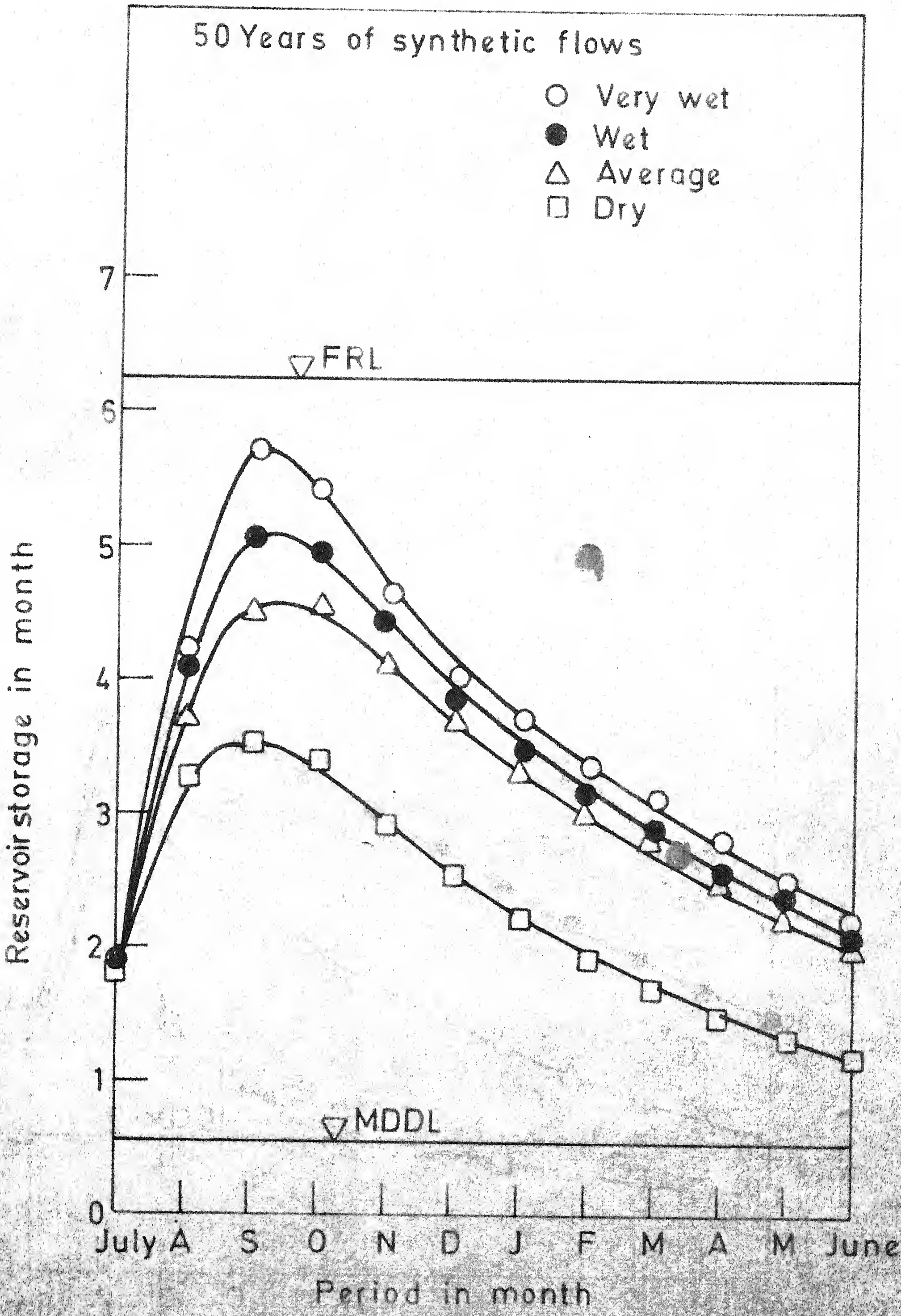


FIG. 6.4.9 RIGID RULES FOR BARGI FOR MODIFIED NWDT AWARD

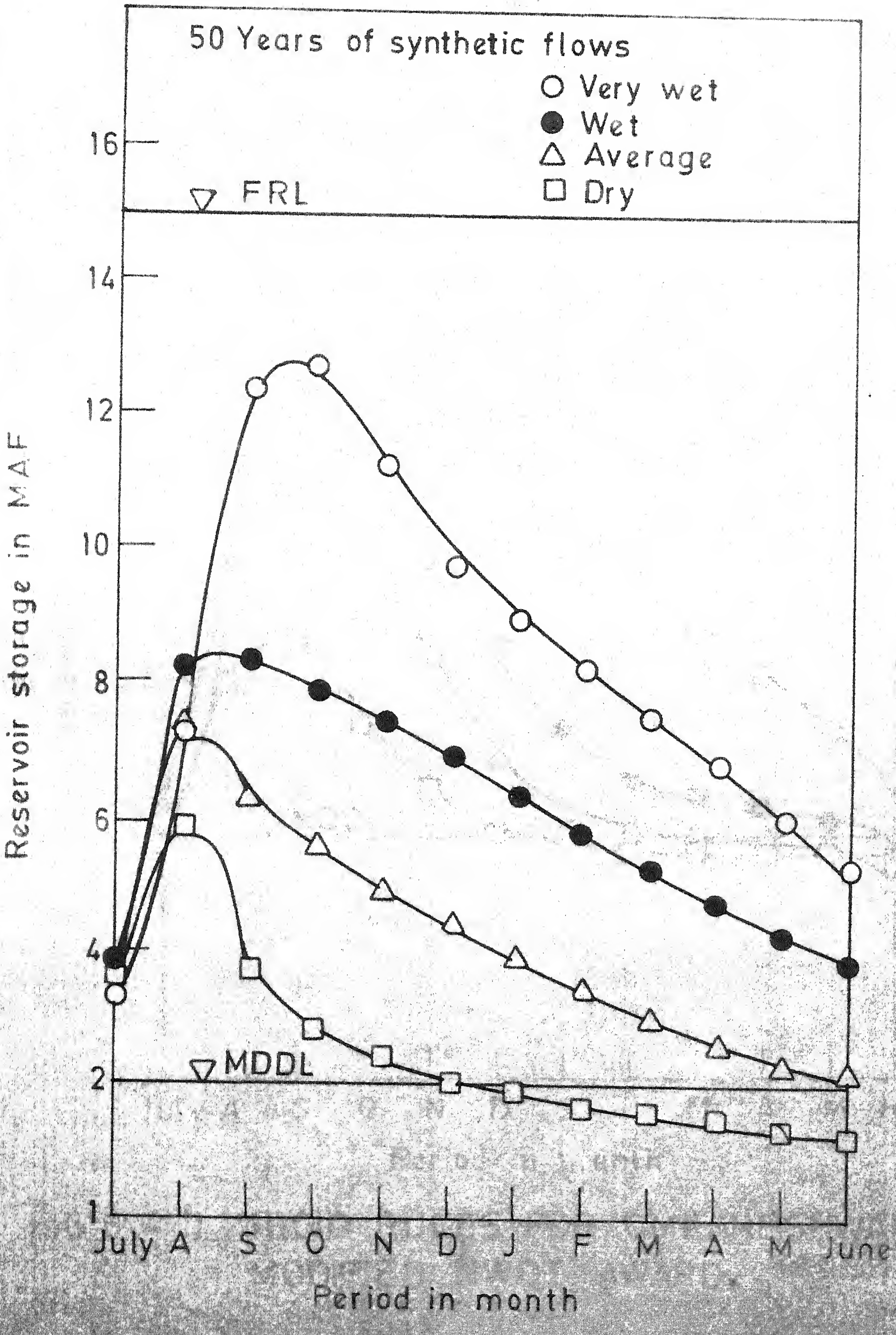


FIG. 6.4.10 RIGID RULES FOR NARMADASAGAR FOR MODIFIED NWDT AWARD

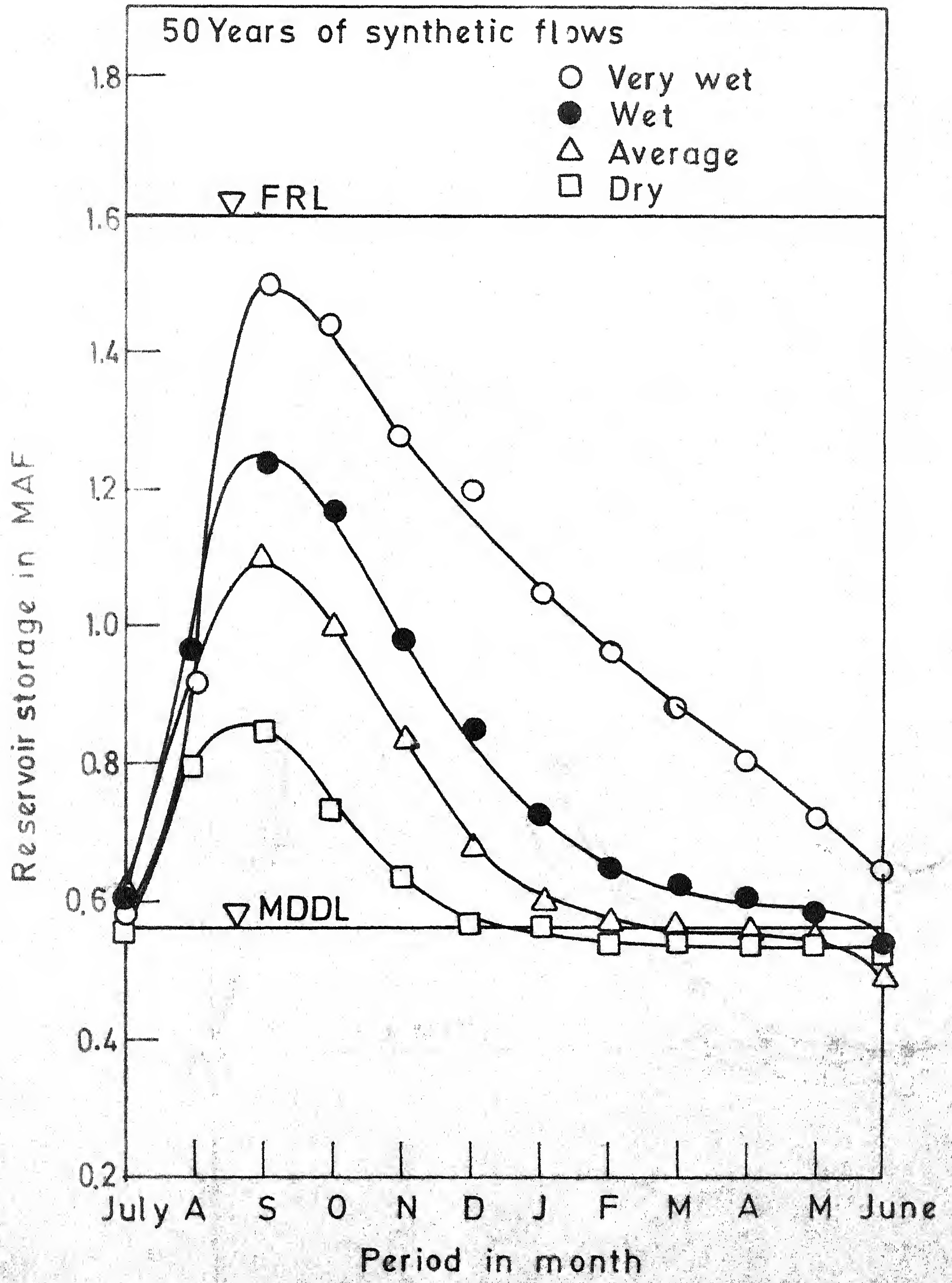


FIG. 6.4.11 RIGID RULES FOR OMKARESHWAR FOR MODIFIED NWDT AWARD

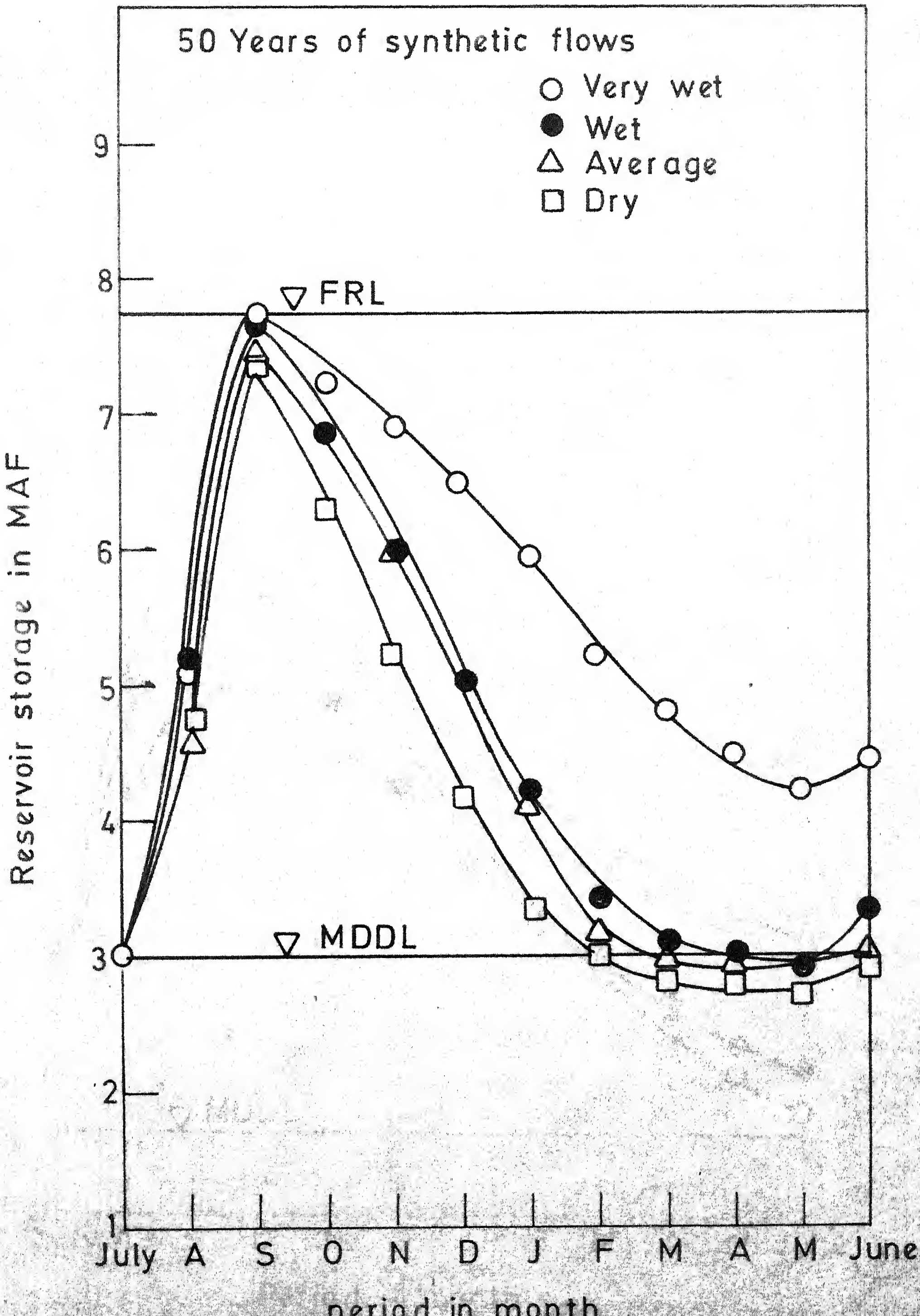


FIG. 6.4.12 RIGID RULES FOR SARDAR SAROVAR FOR MODIFIED NWDT AWARD

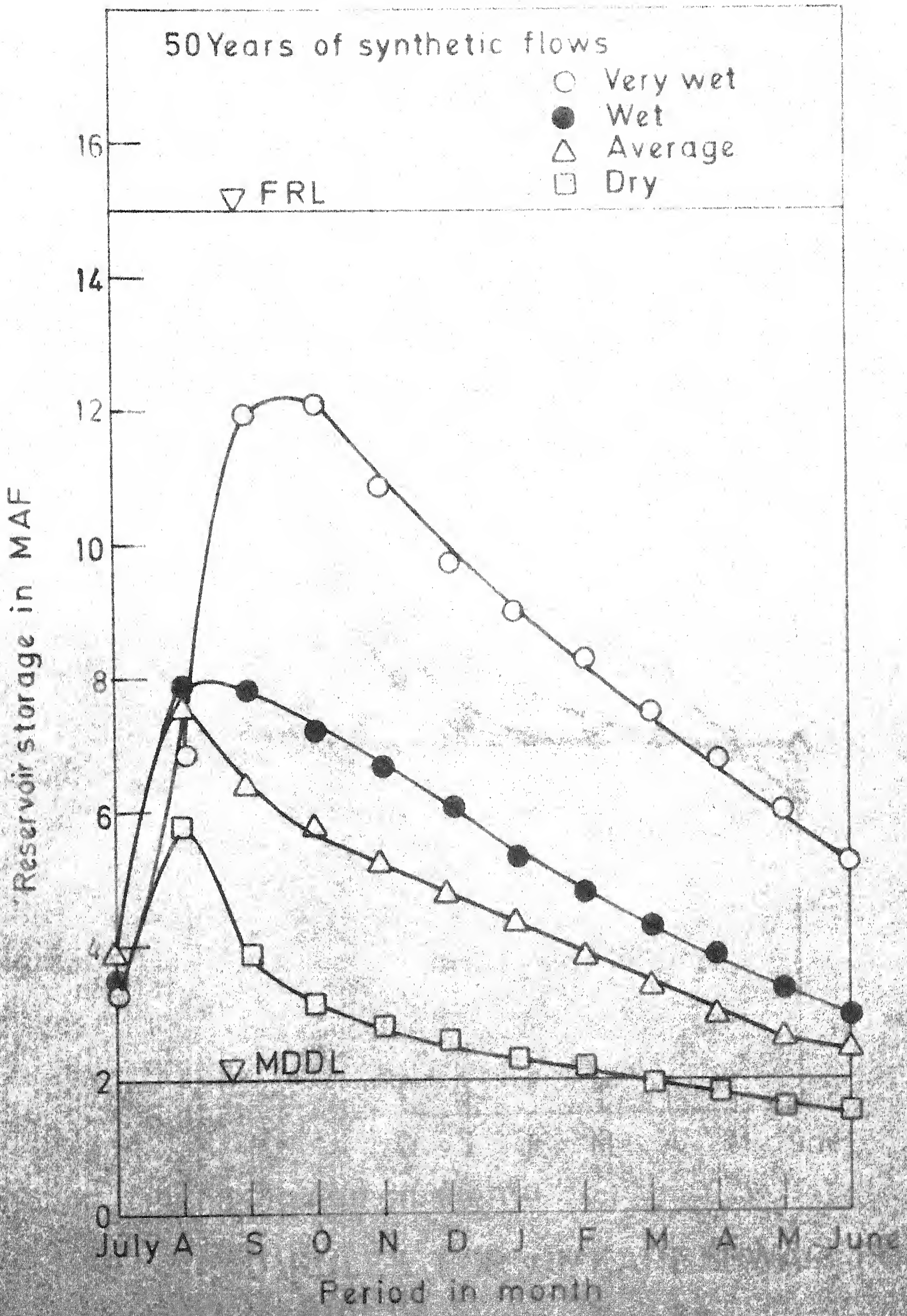


FIG. 6.4.14 RIGID RULES FOR NARMADASAGAR NWDT AWARD

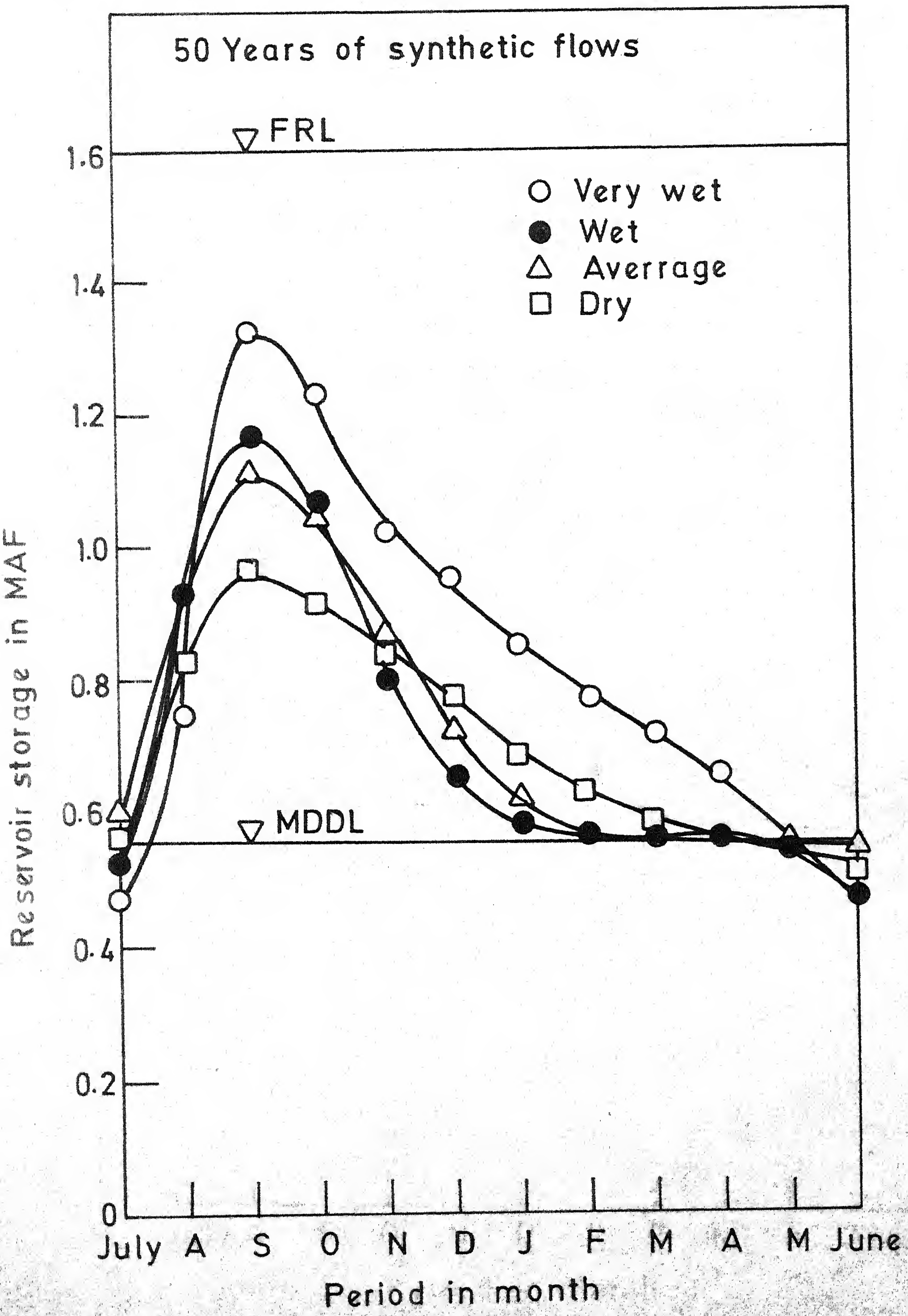


FIG. 6.4.15 RIGID RULES FOR OMKARESHWAR FOR NWDT AWARD

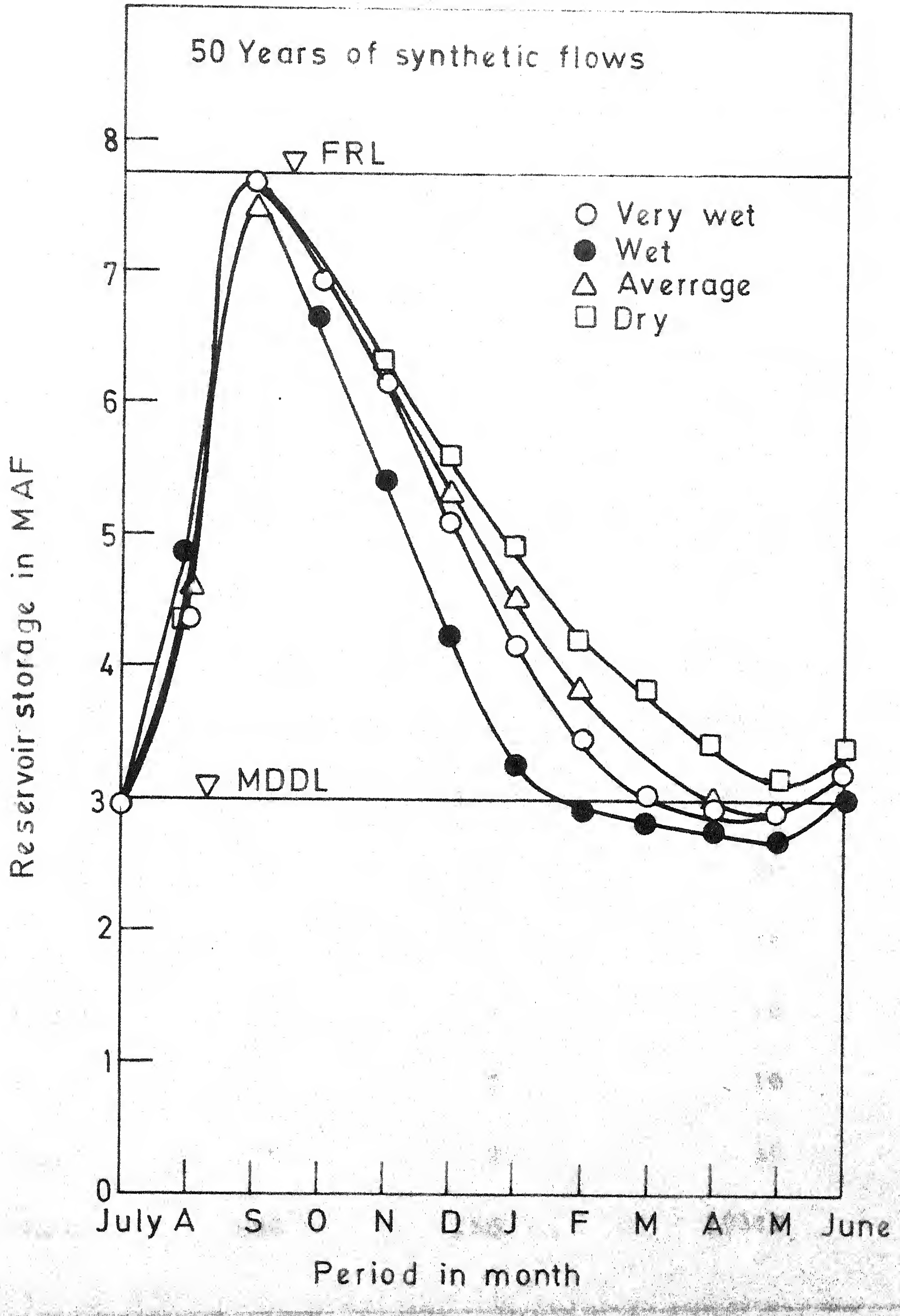


FIG. 6.4.16 RIGID RULES FOR SARDAR SAROVAR FOR NWDT AWARD

TABLE 6.4.51. STATISTICS OF SPILL AT SARDAR SAROVAR FOR 28 YEARS OF HISTORICAL FLOWS FOR MODIFIED NWDT AWARD

Month	Mean cfs	Standard deviation cfs	Maximum spill cfs	Minimum spil cfs
July	42535	6074	157017	0
Aug	14021	2413	92246	99
Sept	36457	247	200000	16
Oct	15681	2238	162977	16
Nov	6712	342	41311	16
Dec	2056	321	12856	16
Jan	14	0	16	0
Feb	9	1	16	0
March	5	2	16	0
April	5	2	16	0
May	5	2	16	0
June	888	158	18342	0

TABLE 6.4.52. STATISTICS OF SPILL AT SARDAR SAROVAR FOR FIRS 50 YEARS OF SYNTHETIC FLOWS FOR MODIFIED NWDT AWARD

Month	Mean cfs	Standard deviation cfs	Maximum spill cfs	Minimum spil cfs
July	26659	1293	147288	16
Aug	10289	1456	128219	99
Sept	23970	3422	213939	16
Oct	6366	907	121456	16
Nov	2025	287	40490	16
Dec	692	97	9751	16
Jan	13	0	16	0
Feb	7	1	16	0
March	3	0	16	0
April	1	0	16	0
May	1	0	16	0
June	497	69	20390	0

TABLE 6.4.53. STATISTICS OF SPILL AT SARDAR SAROVAR FOR SECOND 50 YEARS SYNTHETIC FLOWS FOR MODIFIED NWDT AWARD

Month	Mean cfs	Standard deviation cfs	Maximum spill cfs	Minimum spill cfs
July	38418	17664	144966	0
Aug	14670	2804	105817	99
Sept	31726	1775	143591	16
Oct	10517	2021	142299	16
Nov	4026	772	37540	16
Dec	1393	265	10196	16
Jan	14	0	16	0
Feb	10	1	16	0
March	5	1	16	0
April	4	1	16	0
May	4	1	16	0
June	394	76	19450	0

TABLE 6.4.54. STATISTICS OF SPILL AT SARDAR SAROVAR FOR THIRD 50 YEARS SYNTHETIC FLOWS FOR MODIFIED NWDT AWARD

Month	Mean cfs	Standard deviation cfs	Maximum spill cfs	Minimum spill cfs
July	41964	2678	125789	0
Aug	11901	1633	103290	99
Sept	47285	6014	667986	16
Oct	15532	2986	152976	16
Nov	8175	142	68107	16
Dec	2110	996	14669	16
Jan	14	0	16	0
Feb	10	1	16	0
March	7	2	16	0
April	7	2	16	0
May	5	2	16	0
June	1512	288	36171	0

TABLE 6.4.55. STATISTICS OF SPILL AT SARDAR SAROVAR FOR 28 YEARS OF HISTORICAL FLOWS FOR NWDT AWARD

Month	Mean cfs	Standard deviation cfs	Maximum spill cfs	Minimum spill cfs
July	28261	5436	144337	16
Aug	10013	1556	67842	99
Sept	33108	1379	179343	16
Oct	7829	1504	131306	16
Nov	1638	312	14653	16
Dec	16	0	16	16
Jan	14	0	16	0
Feb	10	2	16	0
March	6	1	16	0
April	3	1	16	0
May	2	0	16	0
June	5	2	16	0

TABLE 6.4.56. STATISTICS OF SPILL AT SARDAR SAROVAR FOR 50 YEARS OF SYNTHETIC FLOWS FOR NWDT AWARD

Month	Mean cfs	Standard deviation cfs	Maximum spill cfs	Minimum spill cfs
July	18851	3625	128305	0
Aug	10334	1970	113920	99
Sept	22139	4258	179382	16
Oct	4216	808	75420	16
Nov	560	105	18284	16
Dec	15	0	16	0
Jan	13	1	16	0
Feb	9	1	16	0
March	7	2	16	0
April	4	2	16	0
May	2	3	16	0
June	4	2	16	0

TABLE 6.4.57. STATISTICS OF SPILL AT SARDAR SAROVAR FOR SECOND 50 YEARS SYNTHETIC FLOWS FOR NWDT AWARD

Month	Mean cfs	Standard deviation cfs	Maximum spill cfs	Minimum spill cfs
July	22733	9411	192653	0
Aug	12129	2315	82696	99
Sept	27031	1063	127788	16
Oct	7355	1412	123265	16
Nov	871	165	15913	16
Dec	16	0	16	16
Jan	12	1	16	0
Feb	9	2	16	0
March	6	1	16	0
April	2	0	16	0
May	2	0	16	0
June	4	1	16	0

TABLE 6.4.58. STATISTICS OF SPILL AT SARDAR SAROVAR FOR THIRD 50 YEARS SYNTHETIC FLOWS FOR NWDT AWARD

Month	Mean cfs	Standard deviation cfs	Maximum spill cfs	Minimum spill cfs
July	20032	4030	85664	0
Aug	10395	1982	87758	99
Sept	41058	7898	249514	16
Oct	9795	1882	143188	16
Nov	2598	497	29411	16
Dec	16	0	16	0
Jan	15	0	16	0
Feb	7	2	16	0
March	7	1	16	0
April	5	1	16	0
May	3	1	16	0
June	4	1	16	0

TABLE 6.4.59. STATISTICS OF SPILL AT SARDAR SAROVAR FOR FLOOD SIMULATION FOR 28 YEARS OF HISTORICAL FLOWS FOR NWDT AWARD

Month	Mean cfs	Standard deviation cfs	Maximum spill cfs	Minimum spill cfs
July	35667	6861	124029	16
Aug	14836	2852	59007	99
Sept	40650	7820	136102	16
Oct	17086	925	136102	16
Nov	8281	203	56549	16
Dec	326	60	2770	16
Jan	270	52	16	0
Feb	9	2	16	0
March	9	2	16	0
April	5	1	16	0
May	9	2	16	0
June	830	157	15082	0

3-hourly maximum spill = 5,42,407 cfs.

TABLE 6.4.60. STATISTICS OF SPILL AT SARDAR SAROVAR FOR FLOOD SIMULATION FOR 28 YEARS OF HISTORICAL FLOWS FOR MODIFIED NWDT AWARD

Month	Mean cfs	Standard deviation cfs	Maximum spill cfs	Minimum spill cfs
July	46419	8930	171710	0
Aug	20984	5589	104186	99
Sept	43812	3949	160135	16
Oct	18980	806	176216	16
Nov	9007	2340	41311	16
Dec	2190	407	12856	16
Jan	14	0	16	0
Feb	9	1	16	0
March	6	2	16	0
April	5	2	16	0
May	5	2	16	0
June	889	213	18342	0

3-hourly maximum spill = 11,00,840 cfs.

6.4.8. Economic evaluation

For determining the net annual benefits achieved from each simulation run, loss functions for irrigation and power are incorporated in the objective function (equation 4.3). The loss functions for irrigation and power are expressed by equations 5.11, and 5.12. The net annual benefits for each simulation is tabulated in Table 6.4.61.

TABLE 6.4.61. ECONOMIC EVALUATION OF THE SYSTEM

Simulation run	Annual benefits in crores	Average	Remarks
1	69.02		
2	62.41	66.37	Modified NWDT award
3	67.80		
4	66.25		
5	77.87		
6	66.84	73.93	NWDT award
7	73.85		
8	77.17		
9	80.13	80.13	NWDT award
10	71.53	71.53	Modified NWDT award

The difference between NWDT and modified NWDT is explained in Section 5.4. From Table 6.4.61, it is seen that the average annual benefits, averaged over four simulation runs or 178 years of simulation, in the case of NWDT award is higher than that in the case of modified NWDT award. It is also noted that flood peak reduction in the case of NWDT at Sardar Sarovar is more than that in the case of modified NWDT. In the former case a flood magnitude of 24,50,000 cusecs gets attenuated to 5,42,407 cusecs, while in the latter case it gets attenuated to 11,00,840 cusecs. It is not easy to calculate benefits due to reduction in flood damage. Hence no attempt has been made here to quantify these benefits.

6.4.9. Comparison of optimizing model results with simulation model results

LPD model gives a wide range in the magnitude of the decision variables as it is run for various configurations and conditions mentioned in Section 6.2. If the design is completely based on these results it may lead to either over optimal or under optimal design. The net benefit from the system varies from 107.5 x 10^7 to 268.22 x 10^7 rupees. Therefore the LPD model is used for preliminary screening purpose.

Further screening of the variables is done by the steepest ascent method. It is seen that the changes in the magnitude of each variable changes the optimal value because of the further screening. The net benefit from the system is reduced to 120.64 x 10^7 rupees.

Results of the simulation model give the performance of the system as the selected system is analysed with a time series inflows. The performance is measured in terms of shortages in irrigation and power. High penalty was introduced for not meeting the target for irrigation and power demand. From the results of simulation it is seen that power shortages are more which means that installed capacity of turbine at various sites required to be reduced. From the simulation results the net benefit from the system varies from 66.37×10^7 to 80.13×10^7 rupees.

CHAPTER 7

SUMMARY AND RECOMMENDATIONS FOR FUTURE WORK

7.1. Summary

A combined use of optimization and simulation techniques proves to be efficient for planning and designing of large water resource systems. This technique is applied to the Narmada river basin in this thesis. The system consists of five serially linked reservoirs located on the main stem of river. A mathematical model is used to represent the system. Four periods in a year are selected for LPD model. This model is run for different cases such as different configurations, different flow conditions and linear and nonlinear objective function to obtain 14 design variables. Deterministic flows are used in the model. This model is planned for preliminary screening purpose.

If the system analysis is based only on the LPD model, the design of system may be overoptimal or underoptimal. Hence the results of the LPD model are needed to be screened further. A range for each variable is assumed on the basis of LPD results for use in the steepest method of sampling. The results of the steepest ascent method are used in simulation study. A set of design variables which gives maximum benefit based on steepest ascent method is selected for simulation study.

Simulation attempts to study the performance of a system for specified operating policies. The operating policies include (i) release policy, (ii) the maximum and minimum

permissible storage for each period and for each reservoir. Simulation study requires long sequences of streamflows. Since only 28 years of streamflow record is available at the gauge sites on Jamtara Mortakka and Garudeshwar, synthetic flows are generated using stochastic hydrology preserving important statistical parameters of the historical streamflows. HEC-4 computer program: 'monthly streamflow simulation' is used to generate 250 years of synthetic flows at each reservoir site, using transferred streamflow data at each reservoir site.

Two types of simulation studies are made (i) monthly simulation and (ii) flood simulation. Four monthly simulation runs are taken for modified NWDT award and for NWDT award, using historical and synthetic flows respectively. Flood simulation study is carried out to find the maximum 3-hourly spill from the terminal reservoir namely Sardar Sarovar. Economic evaluation of the system is also carried out using certain simplified loss functions. Rigid rules are developed for each reservoir using end of month storages. Shortage index and types of shortages for irrigation and power are evaluated at each reservoir site and for each simulation run. The loss functions are necessary to take into account the contingency of not being able to meet irrigation and power targets. Monthly statistics of spills from the terminal reservoir are evaluated for each simulation run.

7.2. Recommendations for Future Work

(i) In the present study, the discontinuous LP (LPD) is used for optimization. It is possible to use stochastic LP technique in this phase.

(ii) The stochastic nature of demand should receive more attention. Further research work is needed to develop the technique for the generation of equally likely sequences of the different types of demands.

(iii) Weekly or ten daily simulation is probably better suited for the system basically operated for conservation purposes. For such simulation studies, adequate techniques of generation of weekly or ten daily sequences of streamflows should be developed.

(iv) There is a lot of scope for improving the loss functions used to account for losses incurred in not meeting target irrigation and power demands.

(v) To reduce the spill, it is recommended to carry out further studies by changing the demand pattern, release policy and maximum permissible storage in each period.

REFERENCES

Ackoff, R.L., 'Progress in the operation research', John Wiley, New York, 1961.

Askew, A.J., 'Chance-constrained dynamic programming and optimization of water resource system', Water Resources Research, Vol. 10(6), 1974, pp. 1099-1106.

Askew, A.J.; Yeh, W.W.G.; and Hall, W.A., 'Use of Monte Carlo technique in the design and operation of multi-purpose reservoir system', Water Resources Research, Vol. 6(4), 1970, pp. 819-816.

Bayer, M.B., 'Nonlinear programming in river basin modeling', Water Resources Research, Vol. 10(2), 1974, pp. 311-317.

Bhaskar, N.R.; and Whitlach, E.E., Jr., 'Derivation of monthly reservoir release policy', Water Resources Research, Vol. 16(6), 1980, pp. 987-993.

Beard, L.R.; Close, E.R.; and Dawdy, D.R., 'Objective determination of safety factor in reservoir design', Journal of Hyd. Div., ASCE, Vol. 96(5), 1970, pp. 1167-1177.

Beard, L.R., 'Functional evaluation of water resource system', International Conference of Water for Peace, Washington, May, 1967.

Becker, L.; and Yeh, W.W.G., 'Optimization of real time operation of multi reservoir system', Water Resources Research, Vol. 10(6), 1974, pp. 1107-1112.

Bellman, R.E.; and Dryfus, S.E., 'Applied dynamic programming', Princeton University Press, Princeton, N.J., 1962.

Biswas, A.K., 'System approach to water management', McGraw Hill, Kogakusha, 1976.

Butcher, W.S., 'Stochastic dynamic programming for optimum reservoir operation', Water Resource Bulletin, Vol. 17(1), 1971, pp. 115-123.

Buras, N., 'Conjuctive use of dams and aquifers', Journal of Hyd. Div., ASCE, Vol. 89(6), 1963, pp. 111-131.

Charnes, A.; Cooper, W.W.; and Symonds, G.H., 'Cost horizon and certainty equivalents: An approach to stochastic programming of heating oils', Management of Science, Vol. 4(3), 1958, pp. 235-263.

Chu, W.S.; and Yeh, W.W.G., 'A nonlinear programming algorithm for real-time hourly reservoir operation', Water Resources Bulletin, Vol. 14(5), 1978, pp. 1048-1063.

Churchman, C.W.; Ackoff, R.L.; and Arnoff, E.L., 'Introduction to operation research', John Wiley, New York, 1957.

Collins, M.A., 'Implementation of an optimization model for operation of a metropolitan reservoir system', Water Resources Bulletin, Vol. 13(1), 1977, pp. 57-80.

Dorfman, R., 'Mathematical models: The multistructure approach', Design of Water Resource Systems, A. Maass, et al., Harvard University Press, Cambridge, 1962.

Dudley, N.J.; and Burt, O.R., 'Stochastic reservoir management and system design for irrigation', Water Resources Research, Vol. 9(3), 1973, pp. 507-522.

Durbin, E.P.; and Kroenke, D.M., 'A out-of-kilter algorithm: A primer', RM 5472-R Rand Corporation Santa Monica, California, 1967.

Eisel, E.M., 'Chance-constrained reservoir model', Water Resources Research, Vol. 8(2), 1972, pp. 339-347.

Eastman, J.; and Revelle, C.S., 'Linear decision rule in reservoir management and design: 3 direct capacity determination and intra-seasonal constraints', Water Resources Research, Vol. 9(1), 1973, pp. 85-88.

Fiering, M.B., 'Queuing theory and simulation in reservoir design', Journal of Hyd. Div., ASCE, Vol. 87(6), 1961, pp. 39-69.

Fiering, M.B., 'Streamflow synthesis', Harvard University Press, Cambridge, Mass., 1967.

Fiering, M.B., 'Forcasts with varying reliability', Journal of Sanitary Div., ASCE, Vol. 95(3), 1969, pp. 629-644.

Fiering, M.B.; and Jackson, B., 'Synthetic streamflows', Water Resources Monograph 1, American Geophysical Union, 1971.

Frederich, A.J.; and Beard, L.R., 'System simulation for integrated use of hydroelectric and thermal power generation', Technical Report No. 33, The Hydrologic Engineering Centre, U.S. Army Corps of Engineers, 1972.

Ford, L.R.; and Fulkerson, D.R., 'Flow in network', Princeton University Press, 1962.

Gablinger, M.; and Loucks, D.P., 'Markov-models for flow regulation', Journal of Hyd. Div., ASCE, Vol. 96(1), 1970, pp. 165-181.

Gani, J.; and Moran, P.A.P., 'The solution of dam equations by Monte Carlo method', Australian Journal of Applied Science, Vol. 6(3), 1955, pp. 267-276.

Hall, W.A., 'Optimal design of a multipurpose reservoir', Journal of Hyd. Div., ASCE, Vol. 90(4), 1964, pp. 141-149.

Hall, W.A.; and Buras, N., 'The dynamic programming approach to water resource development', Journal of Geophysical Research, Vol. 66(2), 1961, pp. 510-520.

Hall, W.A.; Butcher, W.S.; and Esogbue, A., 'Optimization of the operations of a multipurpose reservoir by dynamic programming', Water Resources Research, Vol. 4(3), 1968, pp. 471-477.

Hall, W.A.; Harboe, R.C.; Yeh, W.W.G.; and Askew, A.J., 'Optimum firm power output from a two reservoir system by incremental dynamic programming', Water Resources Centre, University of California, 1969.

Hall, W.A.; and Dracup, J.A., 'Water resources system engineering', Tata McGraw Hill, New Delhi, 1975.

Hall, W.A.; and Roefs, T.W., 'Hydropower project output optimization', Journal of Power Div., ASCE, Vol. 92(1), 1966, pp. 67-79.

Harley, M.J.; and Chidley, T.R.E., 'Deterministic dynamic programming for long term reservoir operating policies', 'Engineering Optimization, Vol. 3, 1978, pp. 63-70.

HEC, 'Reservoir yield', Computer Program 23-J2-L245, August, 1966.

HEC-4, 'Monthly streamflow simulation', Computer Program 723-Xb-2340, Hydrologic Engineering Centre, U.S. Army Corps of Engineers, 1971.

HEC-3, 'Reservoir system analysis for conservation', Computer program 723-Xb-L2030 Users Manual', U.S. Army Corps of Engineers, July, 1974.

Himmelblau, D.M.; and O'Laoghair, D.T., 'Optimal expansion of a water resource system', Academic Press, New York, 1974.

Himmelblau, D.M., 'Optimization of a water resources system by nonlinear programming', Engineering Optimization, Vol. 2, 1977, pp. 229-238.

Hirsch, R.M.; Cohon, J.L.; and Revelle, C.S., 'Gains from a joint operation of multireservoir system', Water Resources Research, Vol. 13(2), 1977, pp. 239-245.

Houcks, M.H.; and Cohon, J.L., 'Sequential explicitly stochastic linear programming models for design and management of multipurpose reservoir system', Water Resources Research, Vol. 14(2), 1978, pp. 161-169.

Houcks, M.H.; and Datta, B., 'Performance evaluation of a stochastic optimization model for reservoir design and management with explicit reliability criteria', Water Resources Research, Vol.

Hook, R.; and Jeeves, T.A., 'Direct research solution of numerical and statistical problem', Journal Ass. Comput. Mach., 8, 1961, pp. 212-229.

Hufschmidt, M.M.; and Fiering, M.B., 'Simulation technique for design of water resources system', Harvard University Press, 1966.

Jacoby, H.D.; and Loucks, D.P., 'Combined use of optimization models in river basin planning', Water Resources Research, Vol. 8(6), 1972, pp. 1401-1414.

Joeres, E.F.; Liebman, J.C.; and Revelle, C.S., 'Operating rules for joint operation of raw water sources', Water Resources Research, Vol. 7(2), 1971, pp. 225-235.

Kottegoda, W.B., 'Statistical methods of river flows synthesis for water resources assessment', Institute of Civil Engineers, 18, 1970.

Lane, M., 'Conditional chance constrained model for reservoir control', Water Resources Research, Vol. 9(4), 1973, pp. 937-948.

Langbein, W.B., 'Queuing theory and water storage', Journal of Hyd. Div., ASCE, Vol. 84(5), 1958, Proc. Paper 1811(1-24).

Larson, R.E., 'State incremental dynamic programming', Elsevier, New York, 1968.

LeClerc, G.; and Marks, D.H., 'Determination of discharge policy for existing reservoir networks under differing objectives", Water Resources Research, Vol. 9(5), 1973, pp. 937-948.

Lettenmair, D.P.; and Burges, S.J., 'Operational assessment of hydrologic methods of long term persistence', Water Resources Research, Vol. 13(1), 1977, pp. 113-124.

Little, J.D.C., 'The use of storage water in a hydroelectric system', Journal of Operations Research Society of America, Vol. 3(1), 1955, pp. 187-197.

Lieu, C.S.; and Tendrow, A.C., 'Multi-lake river system operating rules', Journal of Hyd. Div., ASCE, Vol. 99(9), 1973, pp. 1369-1381.

Loucks, D.P., 'Some comments on linear decision rules and chance constraints', Water Resources Research, Vol. 6(2), 1970, pp. 668-671.

Loucks, D.P.; Stedinger, J.R.; and Haith, D.A., 'Water resource system planning and analysis', Prentice Hall Inc., Englewood, Calif., New Jersey, 1981.

Loucks, D.P.; and Dorfman, P.J., 'An evaluation of some linear decision rules in chance-constrained model for reservoir planning

and operation', Water Resources Research, Vol. 11(6), 1975, pp. 777-782.

Maass, A.; Hufschmidt, M.; Dorfman, P.J.; and Marglin, 'Design of water resources systems', Harvard University Press, Cambridge, Mass., 1962.

Mandelbrot, B.B., 'A fast fractional Gaussian noise generator', Water Resources Research, Vol. 8(5), 1972, pp. 1354-1356.

Mandelbrot, B.B.; and Wallies, J.R., 'Computer experiments with fractional Gaussian model noises', Water Resources Research, Vol. 5(1), 1969, pp. 228-267.

Manne, A., 'Product mix alternatives: Flood control, electric power and irrigation', International Economic Review, Vol. 8(1), 1962, pp. 30-54.

Martinez, E.L.G., 'The effects of data limitations on the application of system analysis to water resources planning in developing countries', Ph.D. Thesis submitted to Colorado State University, 1971.

Matalas, N.C., 'Mathematical assessment of synthetic hydrology', Water Resources Research, Vol. 3(4), 1967, pp. 937-945.

Matalas, N.C.; and Wallies, J.R., 'Statistical properties of multivariate fractional noise process', Water Resources Research, Vol. 17(6), 1971, pp. 1460-1468.

Mawer, P.A.; and Thorn, D., 'Improved dynamic programming procedures to water resources system', Water Resources Research, Vol. 10(2), 1974, pp. 183-190.

McMohan, T.A.; and Miller, D.A., 'Application of the Thomas and Fiering model to a skewed hydrologic data', Water Resources Research, Vol. 17(5), 1971, pp. 1338-1340.

McMahon, T.A.; and Mein, R.G., 'Development in water science series-9', Reservoir Capacity and Yield, Elsevier Scientific Publishing Co., N.Y., 1978.

Meir, W.L., Jr.; and Brightler, C.S., 'An optimization method for branching multi-stage water resource systems', Water Resources Research, Vol. 3(3), 1967, pp. 645-652.

Mejia, J.M.; Rodrigue, I.I.; and Dawdy, D.R., 'Streamflow simulation, the broken line process as a potential model for hydrologic simulation', Water Resources Research, Vol. 8(4), pp. 931-941.

Moreu, D.H.; and Pratt, E.E., 'Weekly and monthly flows in synthetic hydrology', Water Resources Research, Vol. 6(1), 1970, pp. 53-61.

Mobasheri, F.; Harbo, R.C.; and Yeh, W.W.G., 'Optimal policy for reservoir operation', Journal of Hyd. Div., ASCE, Vol. 96(10), 1970, pp. 2297-2307.

Nayak, S.C.; and Arora, S.R., 'Optimal capacities for a reservoir system using linear decision rule', Water Resources Research, Vol. 17(3), 1971, pp. 485-498.

Nayak, S.C.; and Arora, S.R., 'Linear decision rule: A note on control volume being constant', Water Resources Research, Vol. 10(4), 1974, pp. 637-642.

Naylor, T.H., 'Simulation and validation operation research', Ross North Holland Publication Co., 1973.

Nopmogcol, P.; and Askew, A.J., 'Multilevel incremental dynamic programming', Water Resources Research, Vol. 12(6), 1976, pp. 1291-1297.

NWDT, Report of the Narmada Water Dispute Tribunal, Vol. I-V, Published by the Controller of Publications, Delhi, India, 1978.

Opricobic, S.; and Pjordjivic, B., 'Optimal long term control of a multipurpose reservoirs with indirect users', Water Resources Research, Vol. 12(6), 1976, pp. 1286-1290.

Parikh, S.C., 'Linear dynamic decomposition of a multiple-multipurpose reservoirs system', Proceedings of the 4th International Conference of Operation Research, Boston, 1966.

Quimpo, R.G., 'Stochastic analysis of daily river flows', Journal of Hyd. Div., ASCE, Vol. 94(1), 1968, pp. 43-57.

Revelle, C.S.; and Gundelach, J., 'Linear decision rule in reservoir management and design: 5 A general algorithm', Water Resources Research, Vol. 11(2), 1975, pp. 204-207.

Revelle, C.S.; and Kirby, W., 'Linear decision rule in reservoir management and design: 2 performance optization', Water Resources Research, Vol. 6(4), 1970, pp. 1033-1044.

Revelle, C.S.; Joeres, E.; and Kirby, W., 'Linear decision rule in reservoir management and design: 1 development of stochastic model', Water Resources Research, Vol. 5(4), 1969, pp. 767-777.

Roefs, T.G.; and Bodin, L.D., 'Multi-reservoir operation studies', Water Resources Research, Vol. 6(2), 1970, pp. 410-420.

Rogers, P., 'A game theory approach to the problem of international river basins', Water Resources Research, Vol. 5(4), 1969, pp. 767-777.

Schweing, Z.; and Cole, A.J.; 'Optimal control of linked reservoirs', Water Resources Research, Vol. 4(3), 1968, pp. 479-497.

Shen, H.W., 'Stochastic approach to water resources', Water Resources Publications, 1976.

Sigvaldasono, T., 'A simulation model for operating multipurpose, multi-reservoir system', Water Resources Research, Vol. 12(2), 1976, pp. 263-278.

Singh, S.P., 'Synthetic hydrologic information', Journal of Hyd. Div., ASCE, Vol. 105(10), 1979, pp. 1253-1275.

Sobel, M.J., 'Reservoir management', Water Resources Research, Vol. 11(6), 1975, pp. 767-776.

Su, S.V.; and Deininger, R.A., 'Modeling the regulation of lake superior under uncertainty of future water supply', Water Resources Research, Vol. 10(1), 1974, pp. 11-25.

Takeueli, K.; and Moreau, D.H., 'Optimal control of multi-unit interbasin water resources system', Water Resources Research, Vol. 10(3), 1974, pp. 407-414.

Tauxe, G.W.; and Mades, D.M., 'Multi objectives in reservoir operation', Water Resources Research, Vol. 16(1), 1980, pp. 225-238.

Thomas, H.A.; and Burden, R.P., 'Operation research in water quality management', Harvard Water Resources Group, 1973.

Thomas, H.A.; and Watermeyer, A., 'Mathematical models: A stochastic sequential approach', Design of Water Resources System, Mass., 1962, pp. 540-564.

Torabi, M.; and Mobasheri, F., 'A stochastic dynamic programming model for the optimum operation of a multipurpose reservoir', Water Resources Bulletin, Vol. 9(6), 1973, pp. 1089-1099.

Trott, W.J.; and Yeh, W.W.G., 'Optimization of multiple reservoir system', Journal of Hyd. Div., ASCE, Vol. 99(10), 1973, pp. 1865-1884.

TWDB-1, 'System simulation for management of total water resources', Report 118, Texas Water Development Board, 1970.

TWDB-2, 'Economic optimization and simulation techniques for management of regional water resources system', Allocation Model III, TWDB, 1972.

TWDB-3, Computer program SIMLYD-II, TWDB, 1972.

Yevjevich, V.M., 'Stochastic problems in the design of reservoirs', Water Research, 1966, pp. 375-411.

Young, G.K., 'Finding reservoir operating rules', Journal of Hyd. Div., ASCE, Vol. 93(3), 1967, pp. 297-

Young, G.K.; and Pissano, W.C., 'Operational hydrology using residuals', Journal of Hyd. Div., ASCE, Vol. 94(4), 1968, pp. 909-923.

APPENDIX

COST BENEFIT FUNCTIONS OF PROJECTS

NARMADASAGAR

(a) Annual benefit from irrigation: See Figure A1.

$$ABF1 = \left[0.1(P/A, 5, 10) \times (P/F, 5, 10) + 0.02(P/G, 5, 10) \times (P/F, 5, 10) + 0.3(P/A, 5, 20) \times (P/F, 5, 20) + 0.03(P/G, 5, 20) \times (P/F, 5, 20) + 0.9(P/A, 5, 15) \times (P/F, 5, 40) + 0.0007(P/G, 5, 15)(P/F, 5, 40) + 1(P/A, 5, 15)(P/F, 5, 55)\right] \times (A/P, 5, 70),$$

where ABF1 stands for annual benefit factor for irrigation, P/A for series present-worth factor, P/G for uniform-gradient-series present-worth factor, P/F for single-payment present-worth factor, and A/P for capital-recovery factor. Using 5% discount rate and the rate of development as shown in Figure A1, ABF1 works out to be 0.2975. A delta of 2.57 ft at the head regulator and an intensity of irrigation of 135% are assumed in calculating irrigation water requirements. The long term irrigation benefit is taken as Rs. 450/acre irrigated. Therefore the benefit per acre ft of water will be:

$$\frac{450}{2.57 \times 1.35} = \text{Rs. } 129.7/\text{acre ft} \quad \text{or} \quad \text{Rs. } 129.7 \times 10^6/\text{MAF}.$$

Annual benefit from irrigation will be Rs. $129.7 \times 10^6 \times$

ABF1 per MAF, i.e. Rs. $12.97 \times 10^7 \times 0.2975$ = Rs. 3.8564×10^7/MAF.

(b) Annual cost of irrigation works:

Irrigation cost for continuing projects is taken from the Journal of Irrigation and Power, Volume 3, 1978, p. 95, as Rs. 3360/hectare for Madhya Pradesh where Narmadasagar is situated. Assuming a uniform expenditure over 25 year development period and a time horizon of another 45 years, the annual capital cost recovery works out to be Rs. 1.150×10^7/MAF.

(c) Operation, maintenance and replacement (OMR) cost:

OMR cost is assumed as Rs. 7/acre, i.e., Rs. 2.023/acre or Rs. 0.2023×10^7/MAF.

(d) Reservoir cost:

For Narmadasagar, the capital cost is 120.0 crores. The gross storage is 9.9 MAF.

$$\therefore \quad \text{Capital cost/MAF} = \frac{120}{9.9} = \text{Rs. } 12.12 \times 10^7/\text{MAF}$$

Assume a construction period of 10 years, discount rate 5% and total time horizon of 70 years. Using these, the annual capital cost recovery works out to be Rs. 0.485×10^7/MAF.

(e) Annual cost of energy:

At present there is a provision to provide RBPH (river bed power house) at Narmadasagar dam.

Proposed capacity of RBPH: $8 \times 125 = 1000$ MW.

Capital cost chargeable to power = 340 crores.

$$\therefore \text{Cost/kw installed} = \frac{340 \times 10^7}{1000 \times 1000} = \text{Rs. } 3400/\text{kw.}$$

$$\therefore \text{Cost}/10^6 \text{ kw} = \text{Rs. } 340 \times 10^7/10^6 \text{ kw.}$$

Assuming a uniform expenditure over 10 years of installation period and a time horizon of another 60 years, the annual capital cost recovery for hydropower works out to be Rs. $0.00155 \times 10^7/10^6$ kwhr.

(f) Operation, maintenance and replacement (OMR) cost:

OMR cost is assumed as Rs. 34/kw installed, i.e., Rs. $3.4 \times 10^7/10^6$ kw, or Rs. $0.00039 \times 10^7/10^6$ kwhr.

(g) Energy benefit:

The rate of development of energy for Narmadasagar is shown in Figure A2. Using discount rate of 5% and a development period as shown in the figure, the annual benefit from sale of energy at a rate of Rs. 0.50/kwhr comes to Rs. $0.02667 \times 10^7/10^6$ kwhr.

Thus, for Narmadasagar project, it is seen that the annual gross benefit from irrigation is Rs. 3.8564×10^7/MAF, annual cost of irrigation Rs. 1.150×10^7/MAF, OMR cost of irrigation Rs. 0.2023×10^7/MAF and annualized reservoir cost Rs. 0.485×10^7/MAF. Also gross annual benefits from power is

NARMADASAGAR

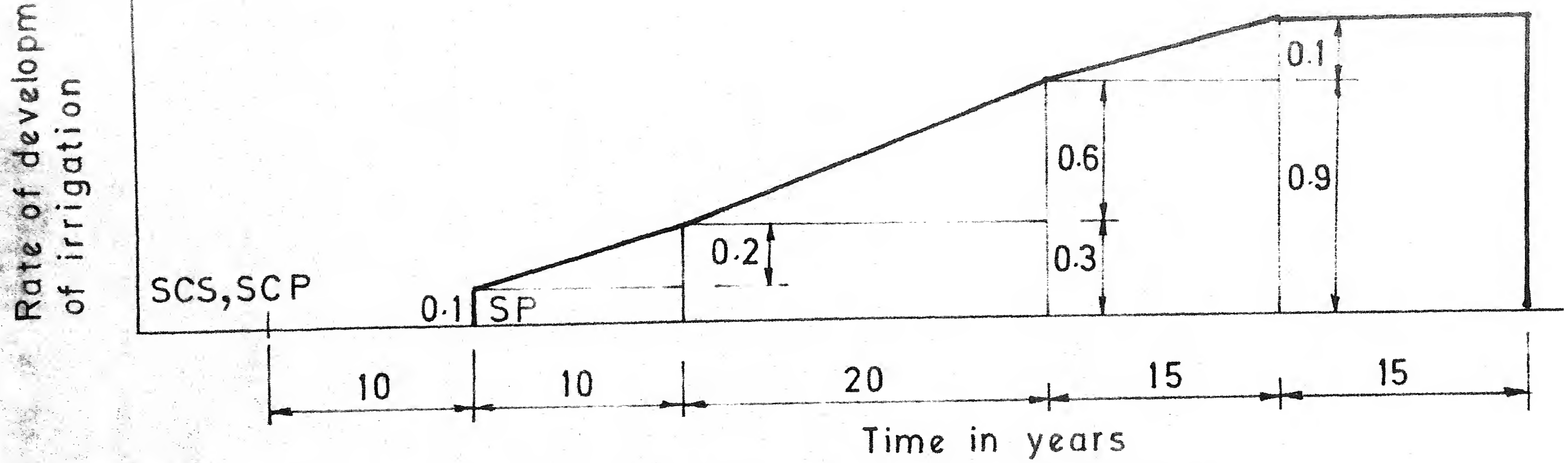


FIG. A1 RATE OF DEVELOPMENT OF IRRIGATION

SCS = Starting of construction of system
SCP = " " " " project
SP = " " production

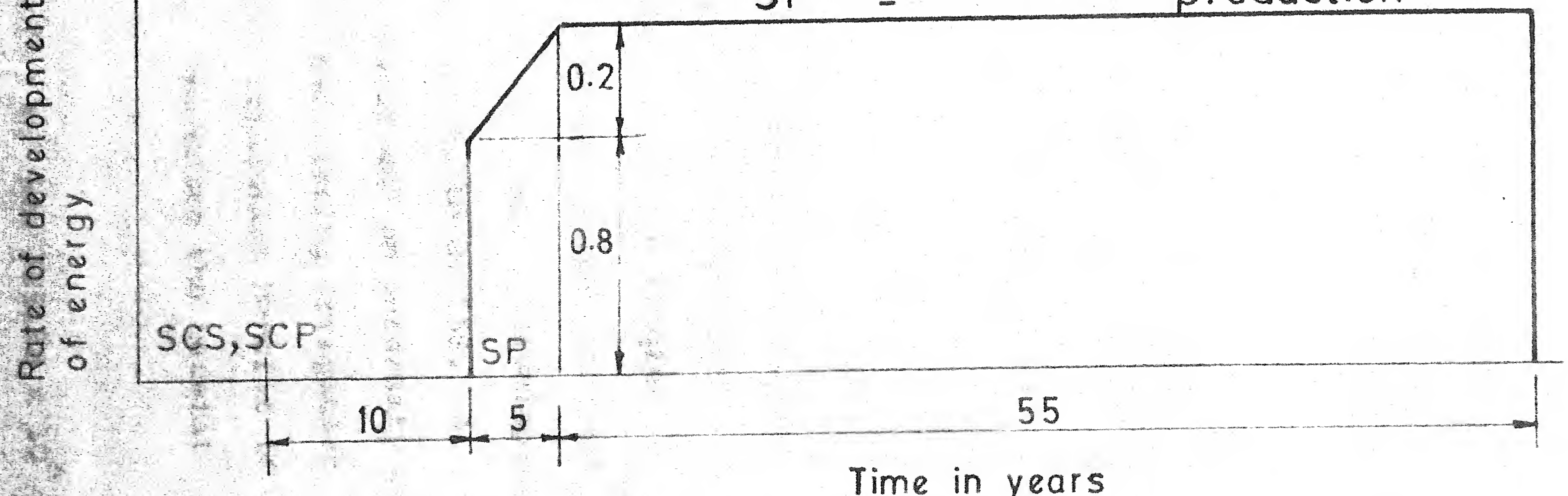


FIG. A2 RATE OF DEVELOPMENT OF ENERGY

Rs. 0.02667 x $10^7/10^6$ kwhr, annual cost of power generation Rs. 0.001296 x $10^7/10^6$ kwhr and OMR cost for power Rs. 0.00039 x $10^7/10^6$ kwhr. Using each of these unit costs and benefits as a guide, cost-capacity curves, benefit-yield curves, OMR cost curves, etc., are prepared and shown in Figures A8 and A12 to A17.

OMKARESHWAR

(a) Annual benefit from irrigation: See Figure A3.

$$\begin{aligned} ABF2 = \Big[& 0.15(P/A, 5, 20)(P/F, 5, 20) + 0.035(P/G, 5, 20) \\ & \times (P/F, 5, 20) + 0.75(P/A, 5, 15)(P/F, 5, 40) \\ & + 0.0067(P/G, 5, 15)(P/F, 5, 40) + 1(P/A, 5, 15) \\ & \times (P/F, 5, 55)\Big] \times (A/P, 5, 70); \end{aligned}$$

where ABF2 stands for annual benefit factor for irrigation, P/A for series present-worth factor, P/G for uniform-gradient-series present-worth factor, P/F for single-payment present-worth factor and A/P for capital-recovery factor. Using 5% discount rate and the rate of development as shown in Figure A3, ABF2 works out to be 0.2158. A delta of 2.57 ft at the head regulator and an intensity of irrigation of 135% are assumed in calculating irrigation water requirements. The long term irrigation benefit is taken as Rs. 437/acre irrigated. Therefore the benefit per acre ft of water will be

$$\frac{437}{2.57 \times 1.35} = \text{Rs. } 125.95/\text{acre ft} \quad \text{or} \quad \text{Rs. } 125.95 \times 10^6/\text{MAF}.$$

Annual benefit from irrigation will be Rs. $125-95 \times 10^6$ $\times$ ABF2 per MAF, i.e., Rs. $12.95 \times 10^7 \times 0.2158 =$ Rs. 2.718×10^7/MAF.

(b) Annual cost of irrigation works:

Irrigation cost for a continuing project is taken from the Journal of Irrigation and Power, Volume 3, 1978, p. 95 as Rs. 3360/hectare for Madhya Pradesh where Omkareshwar is situated. Assuming a uniform expenditure over 15 year development period and total time horizon of 70 years, the annual capital cost recovery works out to be Rs. 0.87×10^7/MAF.

(c) Operation, maintenance and replacement (OMR) cost:

OMR cost is assumed as Rs. 12/acre, i.e., Rs. 3.5/acre ft, or Rs. 0.35×10^7/MAF.

(d) Reservoir cost:

For Omkareshwar, the capital cost is Rs. 76 crores. The gross storage is Rs. 1.216 MAF.

$$\therefore \text{ Capital cost/MAF} = \frac{76}{1.216} = \text{Rs. } 62.5 \times 10^7\text{/MAF.}$$

Assume a construction period of 10 years, discount rate 5% and total time horizon of 70 years. Using these,

the annual capital cost recovery works out to be Rs. 1.530 x 10^7/MAF.

(e) Annual cost of energy:

At present there is a provision to provide RBPH at Omkareshwar dam.

Proposed installed capacity of RBPH: 6 x 65 = 390 MW

Capital cost chargeable to power = 138 crores

$$\therefore \text{Cost/kw installed} = \frac{138 \times 10^7}{390 \times 1000} = \text{Rs. } 3540/\text{kw}$$

Assume a uniform expenditure over 10 years of installation period and total time horizon of 70 years. Using these, the annual capital cost recovery of hydropower works out to be Rs. 0.00099 x $10^7/10^6$ kwhr.

(f) Operation, maintenance and replacement (OMR) cost:

OMR cost is assumed as Rs. 35/kw installed, i.e., Rs. 3.5 x $10^7/10^6$ kw or Rs. 0.00040 x $10^7/10^6$ kwhr.

(g) Energy benefit:

The rate of development of energy for Omkareshwar is shown in Figure A4. Using discount rate of 5%, and, a development period as shown in the figure, the annual benefit from sale of energy at a rate of Rs. 0.50/kwhr comes to Rs. 0.01900 x $10^7/10^6$ kwhr.

Thus, for Omkareshwar project, it is seen that the annual gross benefit from irrigation is Rs. 2.718 x 10^7/MAF, annual cost of irrigation Rs. 0.87 x 10^7/MAF, OMR cost of irrigation Rs. 0.35 x 10^7/MAF and annualized reservoir cost

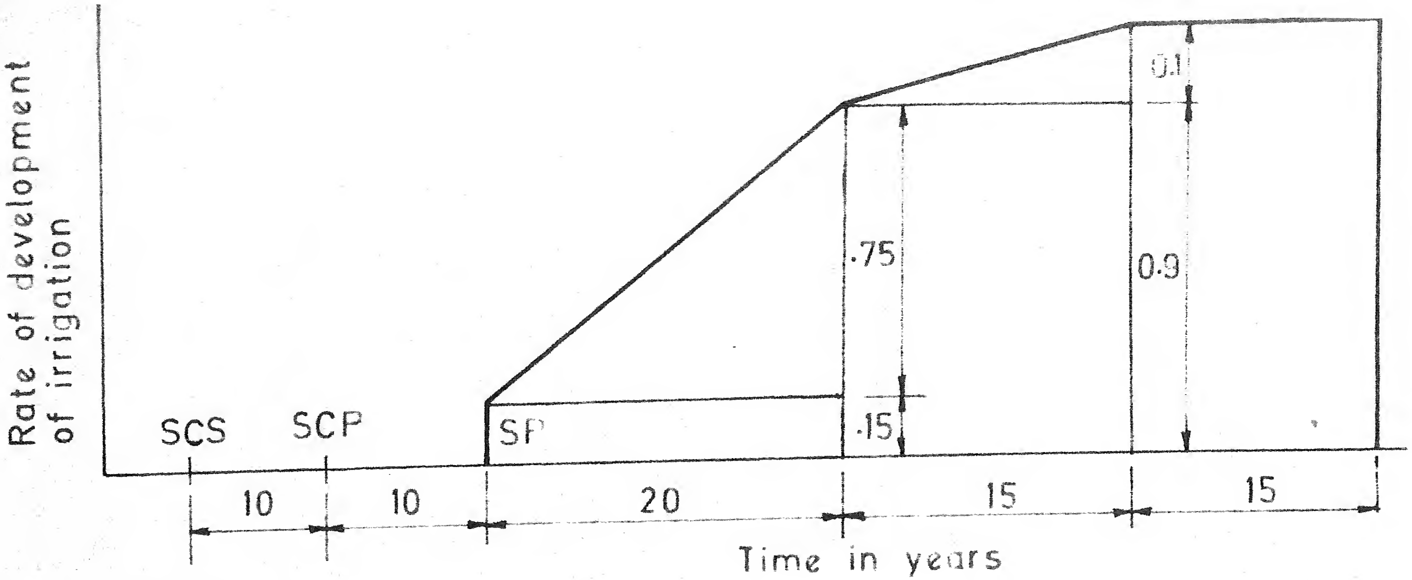
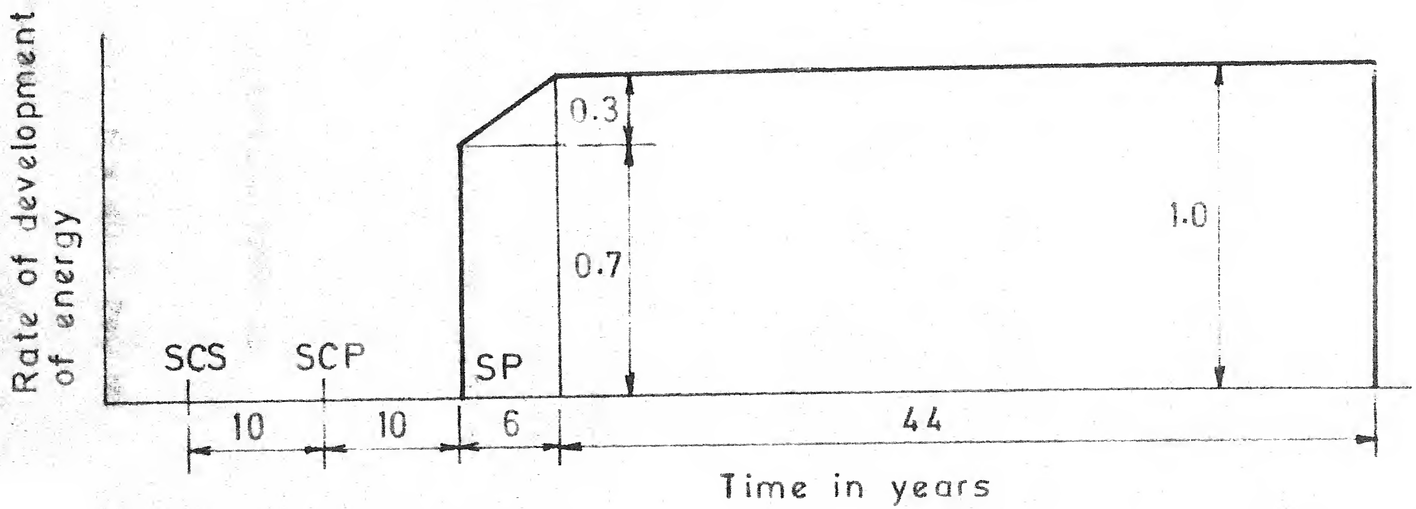


FIG. A 3 RATE OF DEVELOPMENT OF IRRIGATION

SCS = Starting of construction of system
SCP = " " " " project
SP = " " production



Rs. 1.53 x 10^7/MAF. Also gross annual benefits from power is Rs. 0.0190 x $10^7/10^6$ kwhr, annual cost of power generation Rs. 0.00099 x $10^7/10^6$ kwhr, OMR cost of power Rs. 0.00040 x $10^7/10^6$ kwhr. Using each of these unit costs and benefits as guide, cost-capacity curves, benefit-yield curves, OMR cost curves, etc., are prepared and shown in Figures A9 and A12 to A17.

MAHESHWAR

(a) Reservoir cost:

For Maheshwar, the capital cost is 42 crores. The gross storage is 0.4 MAF

$\therefore$ Capital cost/MAF $= \frac{42}{0.4} =$ Rs. 105 x 10^7/MAF

Assume a construction period of 10 years, discount rate 5%, and total time horizon of 70 years. Using these, the annual capital cost recovery works out to be Rs. 2.57 x 10^7/MAF.

(b) Annual cost of energy:

At present there is a provision to provide RBPH at Maheshwar dam.

Proposed installed capacity of RBPH: 6 x 40 = 240 MW

Capital cost of power = 125 crores

$\therefore$ Cost/kw installed $= \frac{125 \times 10^7}{240 \times 1000} =$ Rs. 5200/kw

Assume a uniform expenditure over 10 years of installation period and total time horizon of 70 years. Using these,

the annual capital cost recovery of hydropower works out to be Rs. $0.001455 \times 10^7/10^6$ kwhr.

(c) Operation, maintenance and replacement (OMR) cost:

OMR cost is assumed Rs. 52/kw installed, i.e., Rs. $5.2 \times 10^7/10^6$ kwhr, or, Rs. $0.0005936 \times 10^7/10^6$ kwhr.

(d) Benefit from energy:

The rate of development of energy for Maheshwar is shown in Figure A5. Using discount rate of 5% and a development period as shown in the figure, the annual benefit from sale of energy at a rate of Rs. 0.50/kwhr comes to Rs. $0.002221 \times 10^7/10^6$ kwhr.

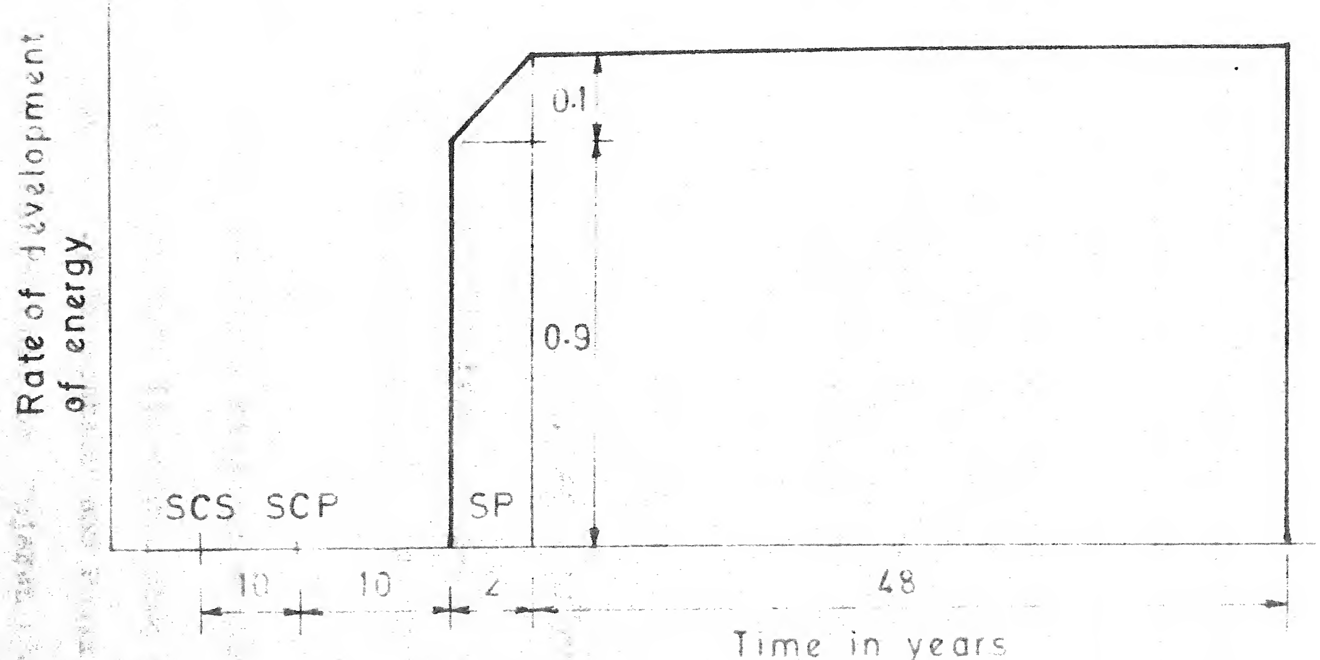
Thus, for Maheshwar project, it is seen that the annual gross benefit from energy is Rs. $0.002221 \times 10^7/10^6$ kwhr, annual cost of power generation is Rs. $0.001455 \times 10^7/10^6$ kwhr. OMR cost for power Rs. $0.00059 \times 10^7/10^6$ kwhr and the annualized reservoir cost is Rs. 2.57×10^7/MAF. Using each of these unit costs and benefits as guide, cost-capacity curves, benefit-yield curves, OMR cost curves, etc., are prepared and shown in Figures A10 and A15 to A17.

SARDAR SAROVAR

(a) Annual benefit from irrigation: See Figure A6.

$$\begin{aligned} ABF3 = \Big[& 0.13(P/A, 5, 10) \times (P/F, 5, 10) + 0.017(P/G, 5, 10) \\ & \times (P/F, 5, 10) + 0.3(P/A, 5, 20) \times (P/F, 5, 20) \\ & + 0.035(P/G, 5, 20)(P/F, 5, 20) + 1(P/A, 5, 30) \\ & \times (P/F, 5, 40) \Big] \times (A/P, 5, 70); \end{aligned}$$

MAHESHWAR



SCS = Starting of construction of system
SCP = " " " " project
SP = " " production

FIG. A5 RATE OF DEVELOPMENT OF ENERGY

where ABF3 stands for annual benefit factor for irrigation, P/A for series present-worth factor, P/G for uniform-gradient-series present-worth factor, P/F for single-payment present-worth factor, and A/P for capital-recovery factor. Using 5% discount rate and rate of development as shown in Figure A6., ABF3 works out to be 0.32. A delta of 2.57 ft at the head regulator and an intensity of irrigation of 135% are assumed in calculating irrigation water requirements. The long term irrigation benefit is taken as Rs. 625/acre irrigated. Therefore the benefit per acre ft will be:

$$\frac{625}{2.57 \times 1.35} = \text{Rs. } 180/\text{acre ft, or,}$$

$$\text{Rs. } 180 \times 10^6/\text{MAF.}$$

Annual benefit from irrigation will be Rs. $180 \times 10^6 \times$ ABF3 per MAF, i.e., Rs. $18 \times 10^7 \times 0.32$ = Rs. 5.763×10^7/MAF.

(b) Annual cost of irrigation works:

Irrigation cost for continuing projects is taken from the Journal of Irrigation and Power, Volume 3, 1978, p. 95 as Rs. 2790/hectare for Gujarat where Sardar Sarovar is situated. Assuming a uniform expenditure over 20 years development period and a time horizon of another 50 years,

the annual capital cost recovery works out to be Rs. 1.052×10^7/MAF.

(d) Operation, maintenance and replacement (OMR) cost:

OMR cost is assumed Rs. 10/acre, i.e., Rs. 2.89×10^6/MAF, or, Rs. 0.2890×10^7/MAF.

(d) Reservoir cost:

For Sardar Sarovar, the capital cost is 200 crores. The gross storage is 7.75 MAF.

$$\therefore \text{ Capital cost/MAF} = \frac{200}{7.75} = \text{Rs. } 25.80 \times 10^7\text{/MAF.}$$

Assume a construction period of 10 years, discount rate 5%, and total time horizon of 70 years. Using these, the annual capital cost recovery works out to be Rs. 1.03×10^7/MAF.

(e) Annual cost of energy:

At present there are provisions for RBPH and CHPH at Sardar Sarovar. In final stage the energy from RBPH will become nil.

Proposed installed capacity of RBPH and CHPH: 1200 MW

(RBPH $5 \times 150 = 750$ MW; CHPH $6 \times 75 = 450$ MW)

Capital cost chargeable to power = 276 crores

$$\therefore \text{ Cost/kw installed} = \frac{276 \times 10^7}{1200 \times 1000} = \text{Rs. } 2300\text{/kw.}$$

Assuming a uniform expenditure over 10 years of installation period and a time horizon of another 60 years, the annual capital cost recovery for hydropower works out to be Rs. $0.00105 \times 10^7/10^6$ kwhr.

(g) Operation, maintenance and replacement (OMR) cost:

OMR cost is assumed as Rs. 23/kw installed, i.e. 2.3 x $10^7/10^6$ kw, or, Rs. 0.00026 x $10^7/10^6$ kwhr.

(h) Energy benefit:

The rate of development for energy for Sardar Sarovar is shown in Figure A7. Using discount rate of 5% and a development period as shown in the figure, the annual benefit from sale of energy at the rate of 0.35/kwhr comes to Rs. 0.01867 x $10^7/10^6$ kwhr.

Thus, for Sardar Sarovar project, it is seen that the annual gross benefit from irrigation is Rs. 5.763 x 10^7/MAF, annual cost of irrigation Rs. 1.053 x 10^7/MAF, OMR cost Rs. 0.2890 x 10^7/MAF, and annualized reservoir cost Rs. 1.03 x 10^7/MAF. Also gross annual benefit from power is Rs. 0.01867 x $10^7/10^6$ kwhr, annual cost of power generation Rs. 0.00105 x $10^7/10^6$ kwhr and OMR cost for power Rs. 0.00026 x $10^7/10^6$ kwhr. Using each of these unit costs and benefits as guide, cost-capacity curves, benefit-yield curves, OMR cost curves etc., are prepared and shown in Figures A11 to A17.

EXTRACT FROM THE NWDT AWARD

(1) In the event of the available utilisable waters for allocation in any water year from 1st of July to 30th of June of the next calender year falling short of 28 MAF, the shortage should be shared between various States in the ratio of 73 for Madhya Pradesh, 36 for Gujarat, 1 for Maharashtra, and 2 for Rajasthan.

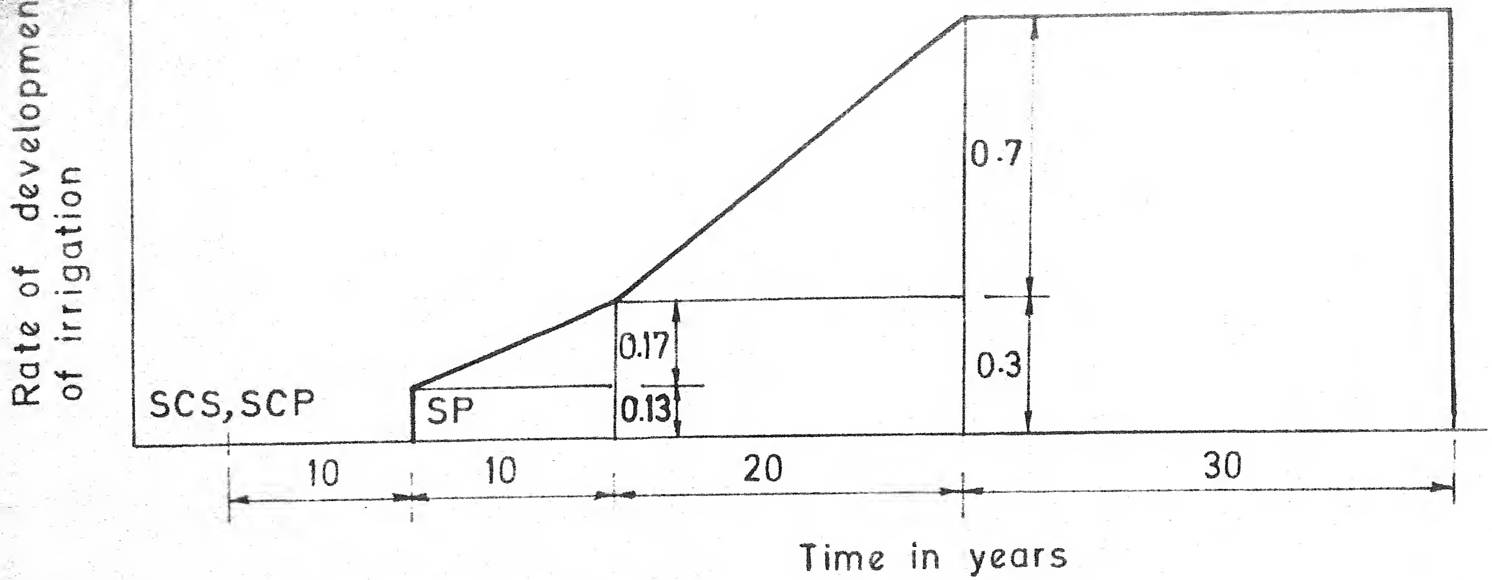


FIG. A6 RATE OF DEVELOPMENT OF IRRIGATION

SCS = Starting of construction of system
SCP = " " " " project
SP = " " projection

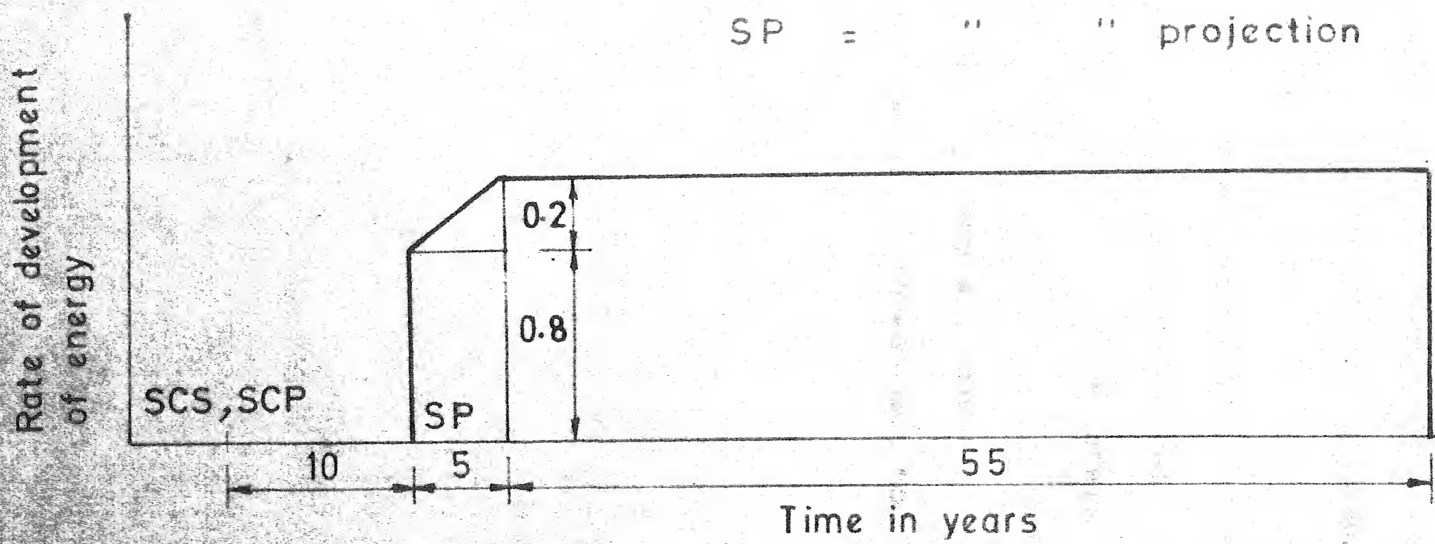
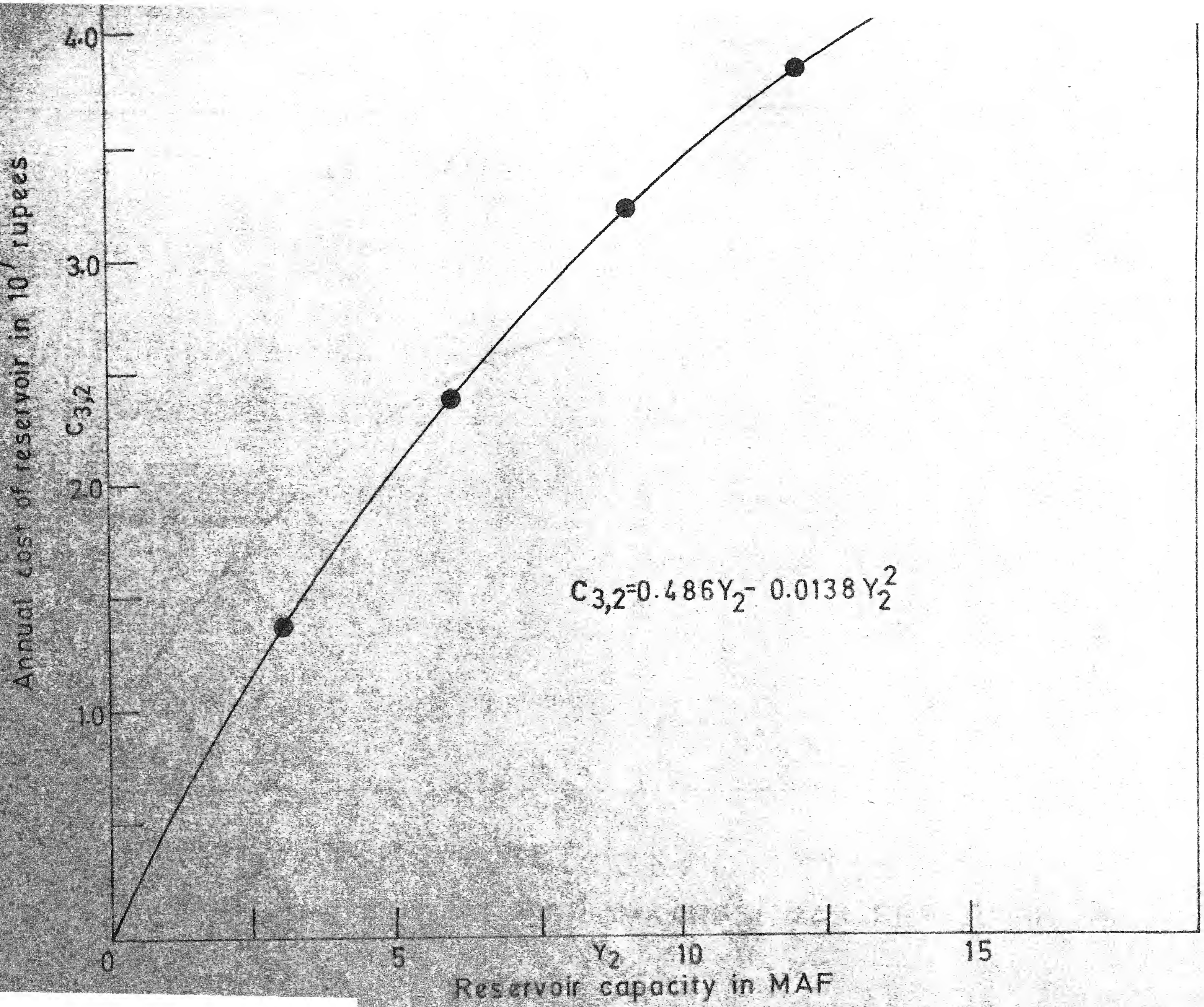


FIG. A7 RATE OF DEVELOPMENT OF ENERGY

(2) The utilisable flow of Narmada in excess of 28 MAF in any water year, i.e., from 1st of July to 30th of June of next calender year is apportioned in the following ratios of allocation, i.e., 73 for Madhya Pradesh, 36 for Gujarat, 1 for Maharashtra, and 2 for Rajasthan.

(3) The available utilisable water in a water year will include the waters carried over from the previous water year as assessed on the 1st of July on the basis of stored waters available on that date.

(4) The available utilisable waters on any date will be inclusive of return flows and exclusive of losses due to evaporation from various reservoirs.



Annual cost of reservoir in 10^7 rupees
$C_{3,2}$
4.0
3.0
2.0
1.0
0
5
10
15
Y_2
Reservoir capacity in MAF
$C_{3,2} = 0.486 Y_2 - 0.0138 Y_2^2$

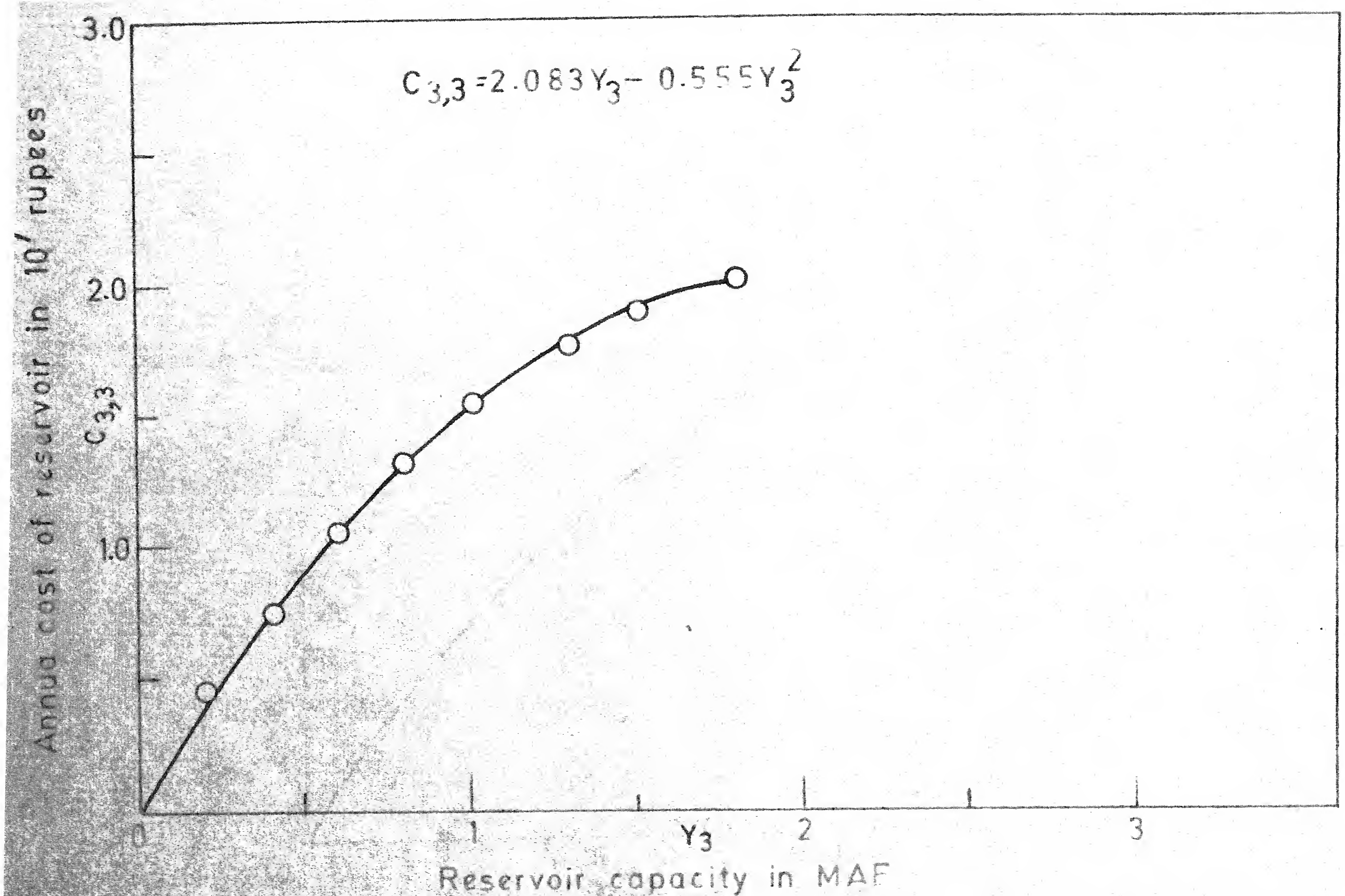


FIG. A9 ANNUAL COST OF OMKARESHWAR RESERVOIR

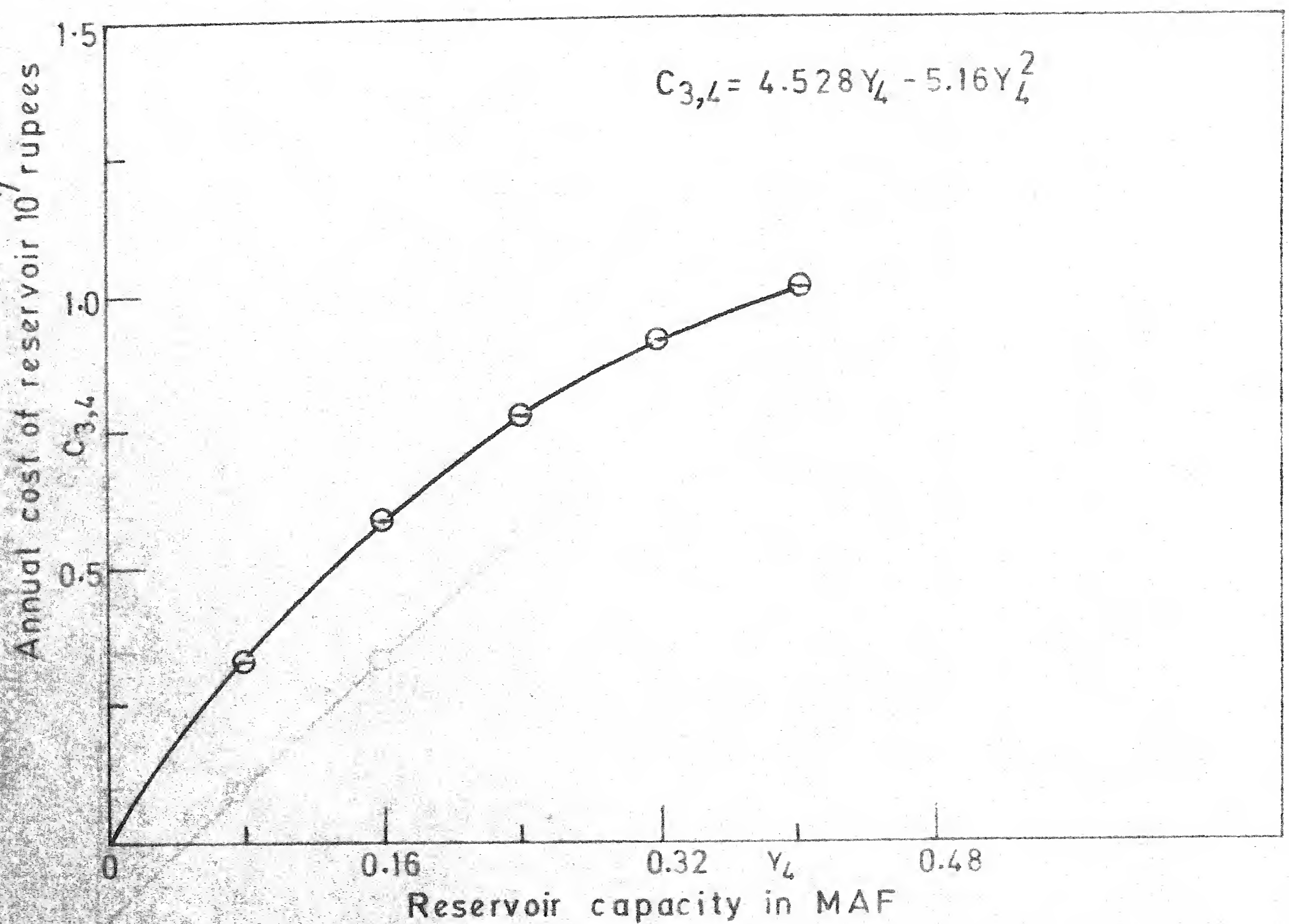


FIG. A10 ANNUAL COST OF MAHESHWAR RESERVOIR

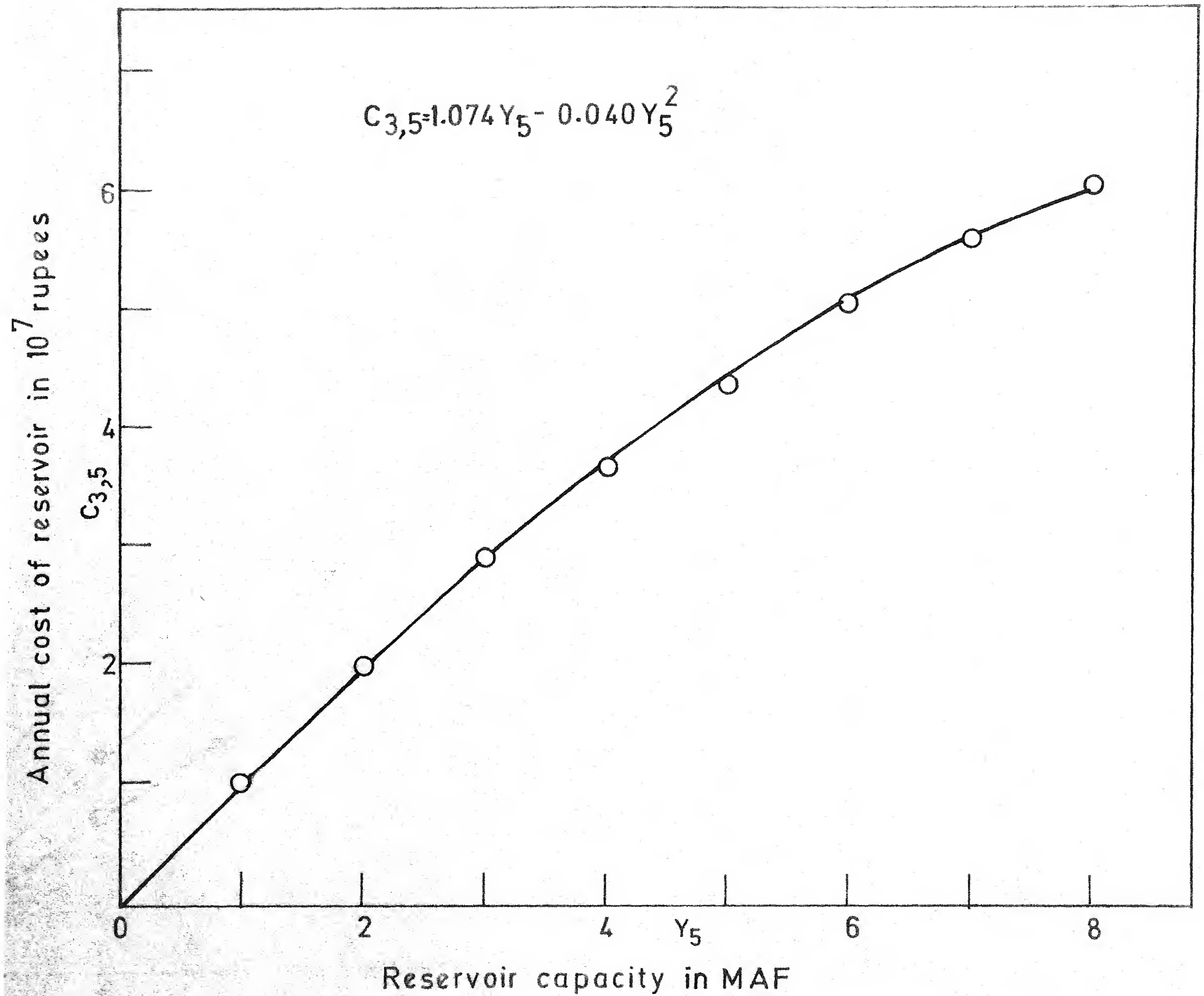
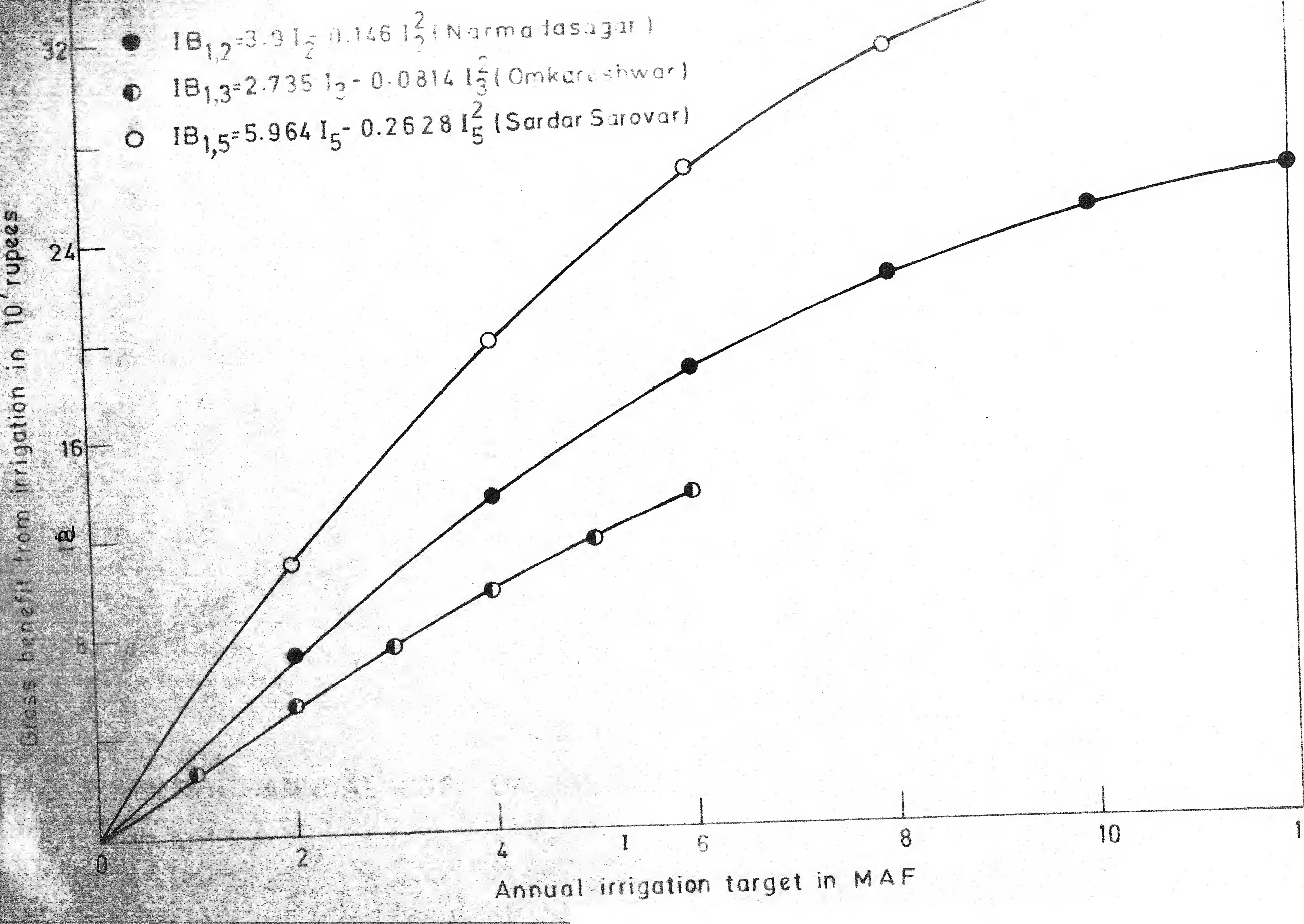


FIG. A11 ANNUAL COST OF SARDAR SAROVAR



$IB_{1,2} = 3.9 I_2 - 0.146 I_2^2$ (Narmadasagar)
$IB_{1,3} = 2.735 I_3 - 0.0814 I_3^2$ (Omkareshwar)
$IB_{1,5} = 5.964 I_5 - 0.2628 I_5^2$ (Sardar Sarovar)
32
24
16
8
0
2
4
6
8
10
Gross benefit from irrigation in 10^7 rupees
Annual irrigation target in MAF

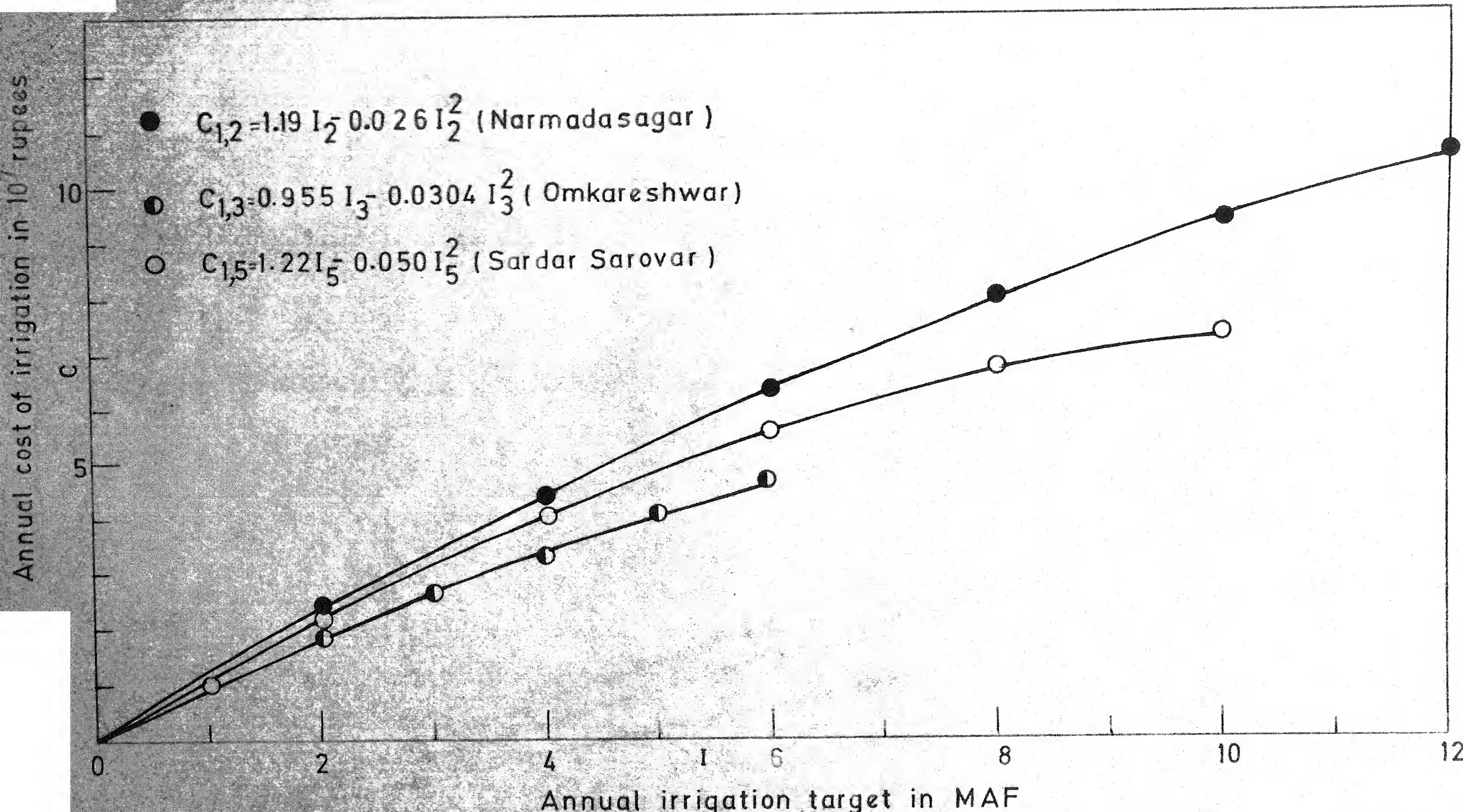


FIG. A 13 ANNUAL COST OF IRRIGATION AT VARIOUS RESERVOIR SITES

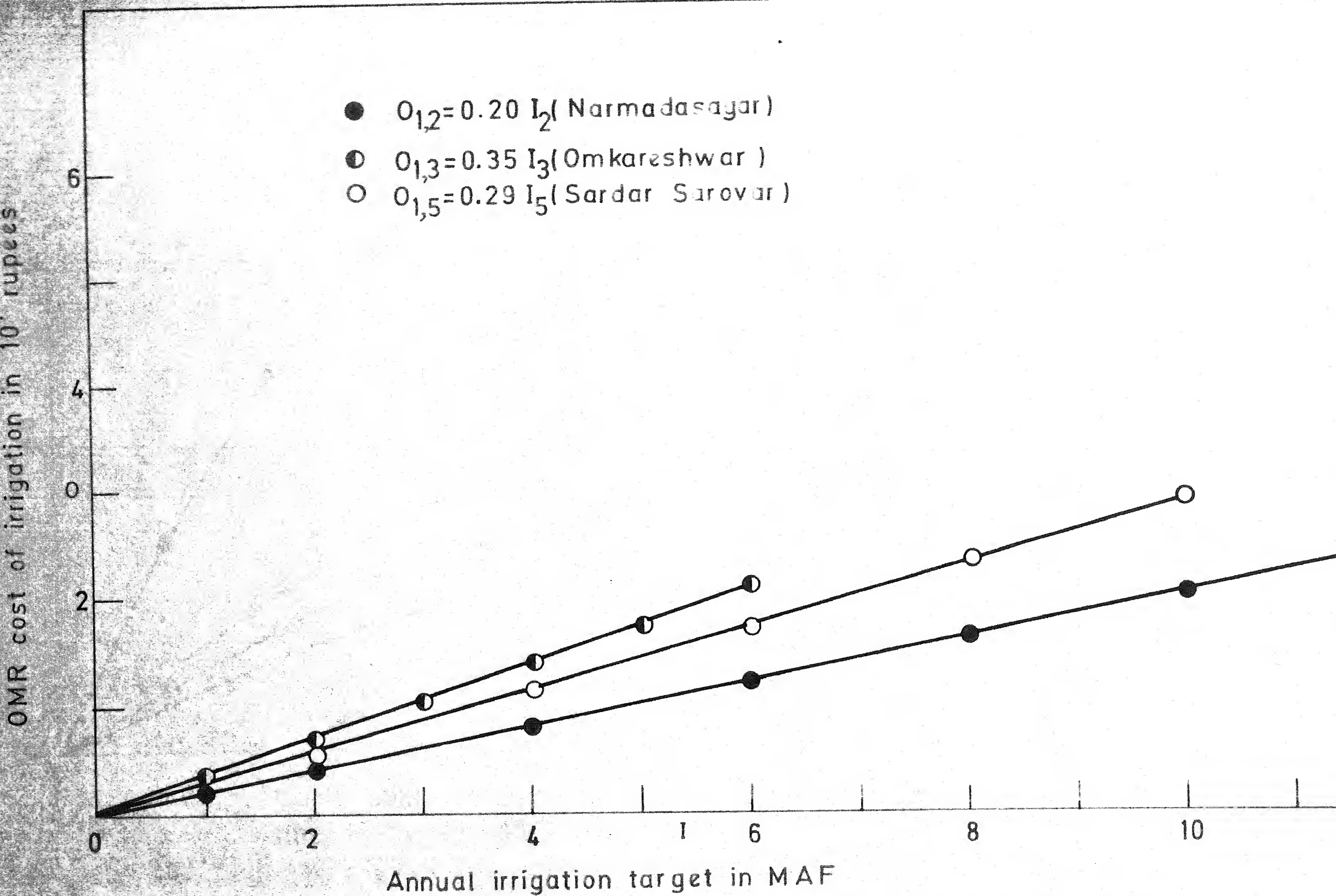


FIG. A14 OMR COST OF IRRIGATION AT VARIOUS RESERVOIR SITES

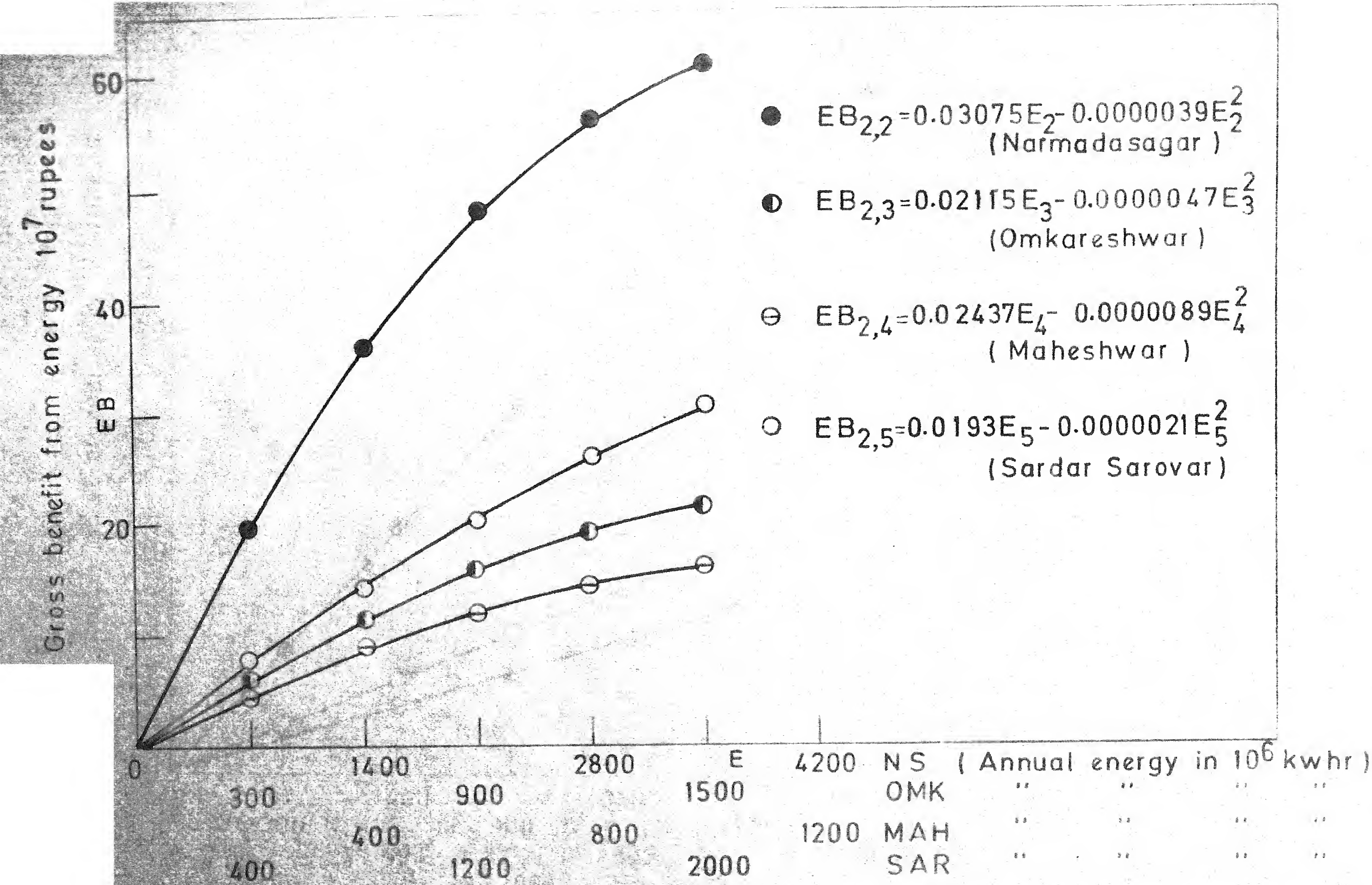


FIG. A 15 GROSS BENEFIT FROM ENERGY AT VARIOUS RESERVOIR SITES

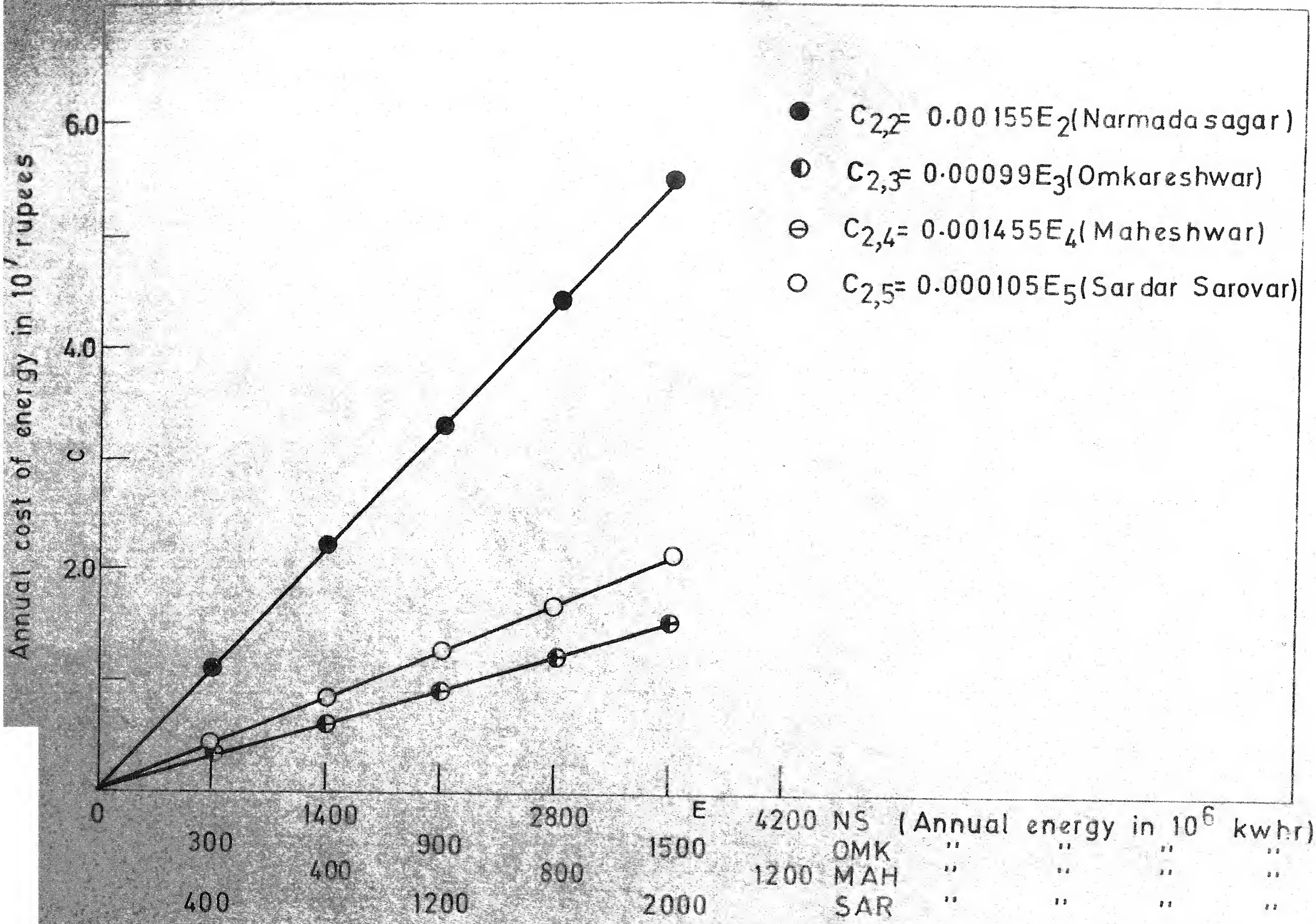


FIG. A 16 ANNUAL COST OF ENERGY AT VARIOUS RESERVOIR SITES

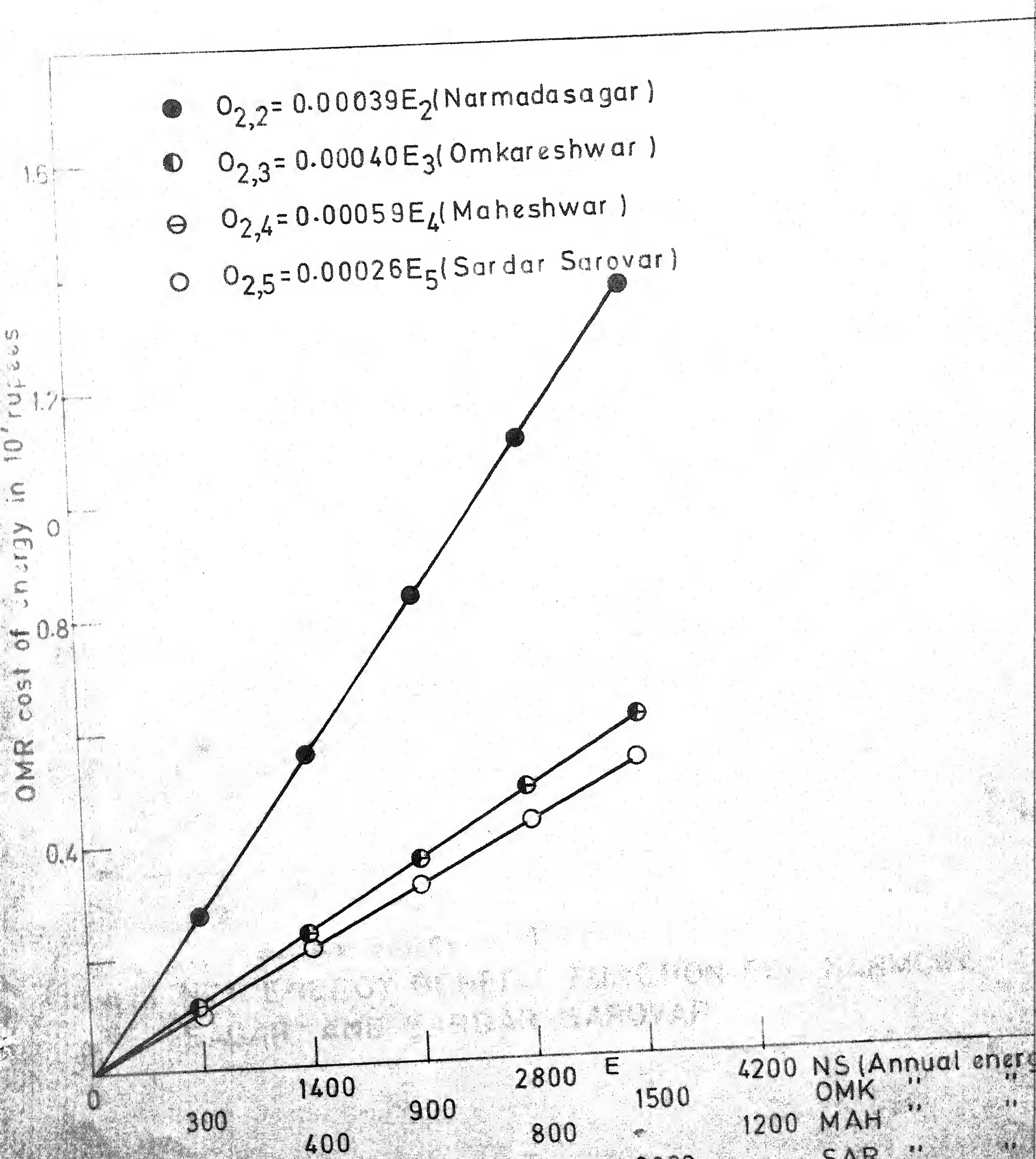


FIG. A17 OMR COST OF ENERGY AT VARIOUS RESERVOIRS

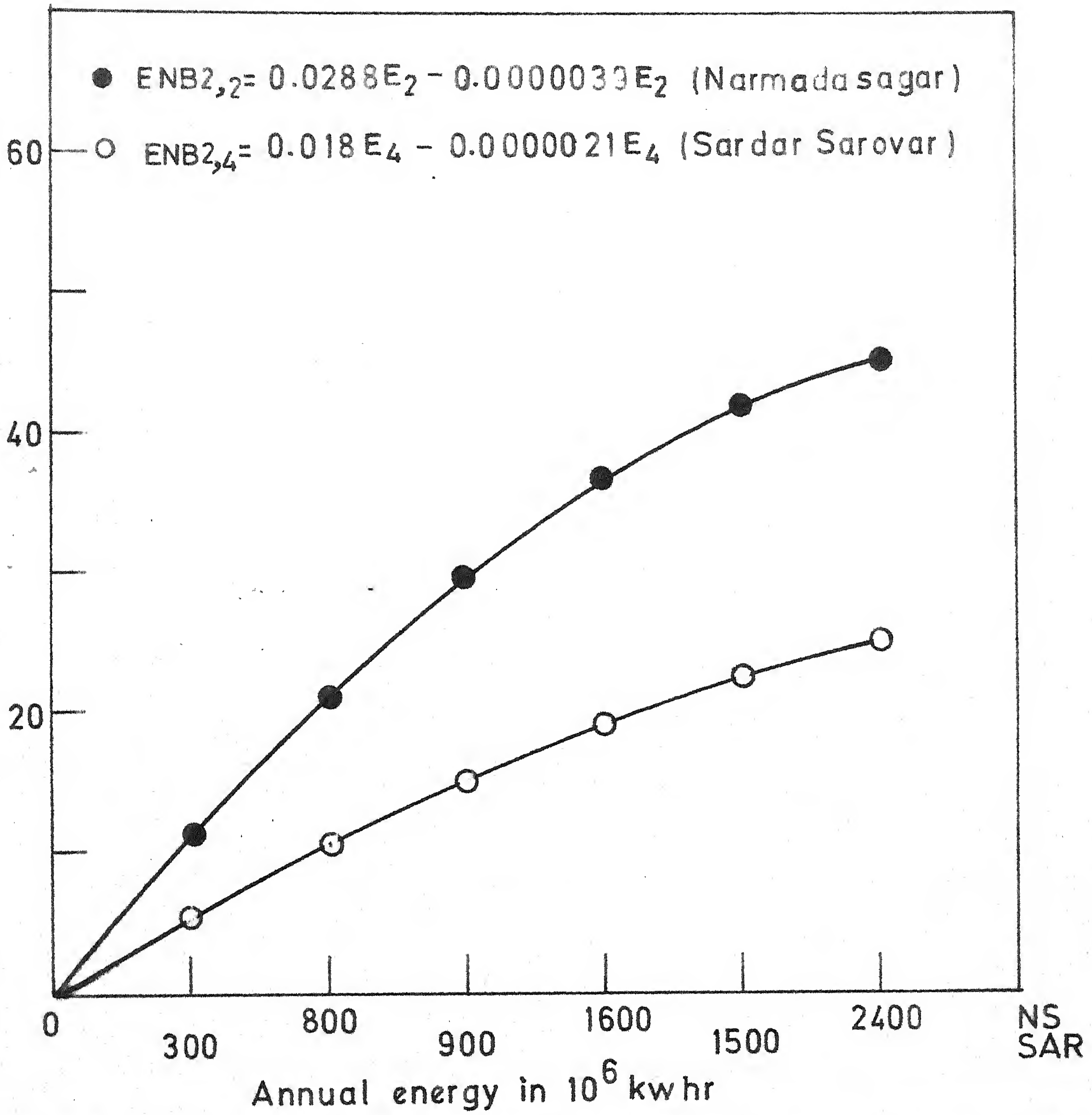


FIG.A18 NET ENERGY BENEFIT FUNCTION FOR NARMODA SAGAR AND SARDAR SAROVAR

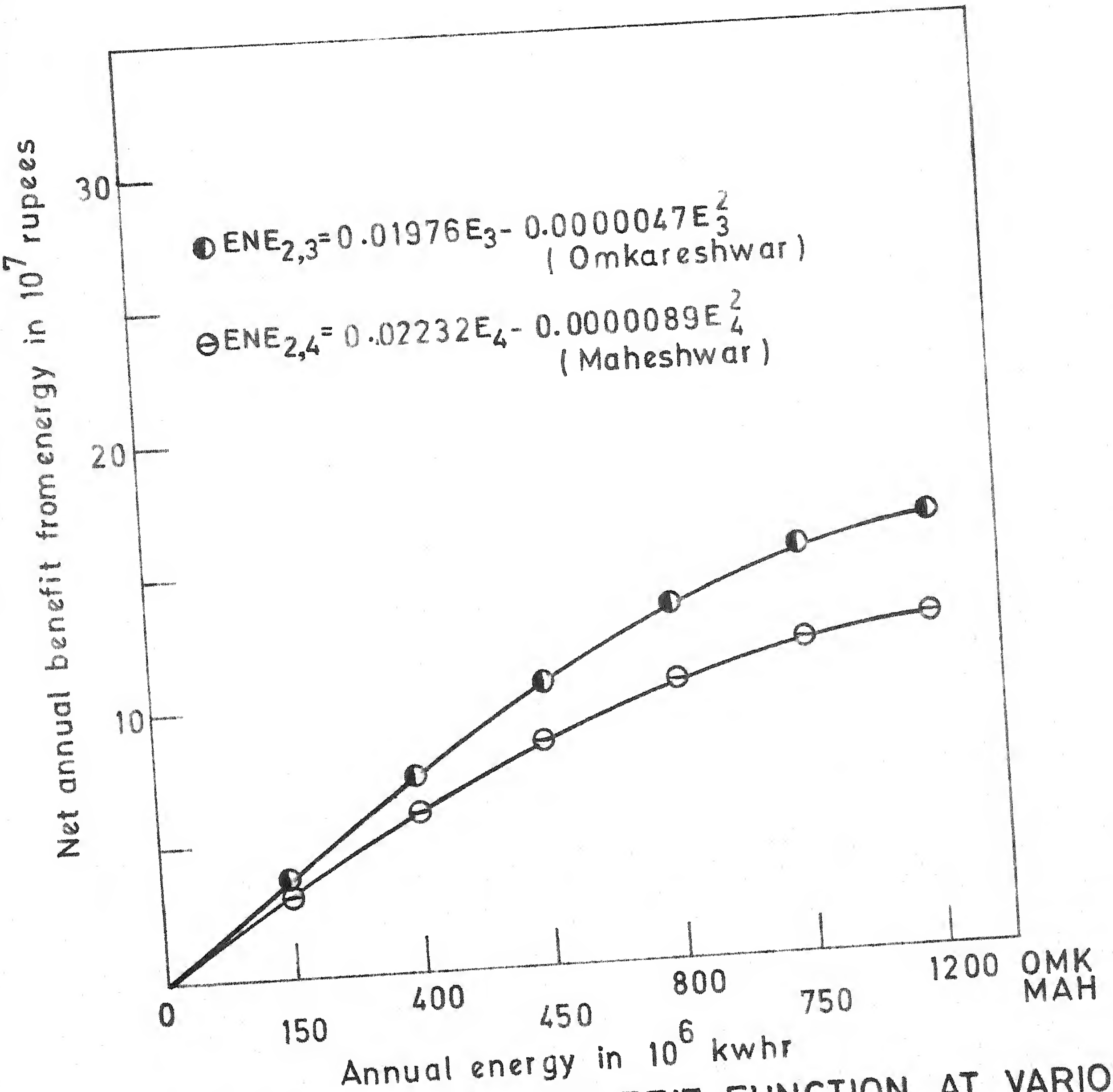


FIG. A19 NET ENERGY BENEFIT FUNCTION AT VARIOUS RESERVOIR SITES

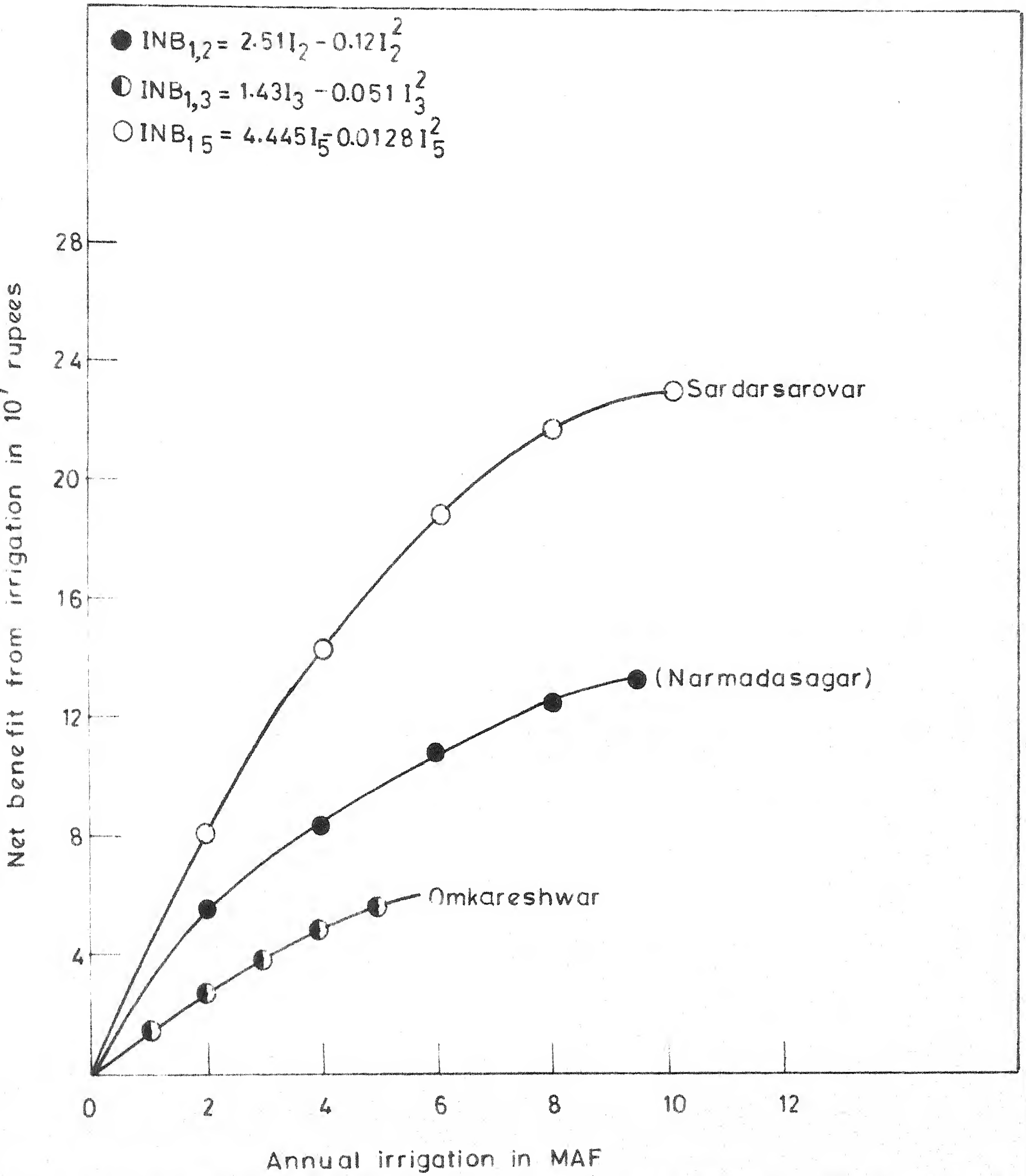


FIG. A 20 NET IRRIGATION BENEFIT FUNCTIONS AT VARIOUS RESERVOIR SITES